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THERMO-PHYSIOLOGICAL RESPONSES OF SAILORS IN A DISABLED SUBMARINE WITH INTERIOR CABIN TEMPERATURE AND HUMIDITY SLOWLY RISING AS PREDICTED BY COMPUTER SIMULATION TECHNIQUES

United States Army
Medical Research & Materiel Command

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14. ABSTRACT

Sailor's thermo-physiological responses to the unrelenting heat accumulation possibilities of a disabled submarine were simulated with USARIEM thermoregulatory models. The modeling indicates a sedentary lightly clad sailor, waiting for rescue, would begin to experience thermo-regulatory failure, i.e., a rapid rise in body temperature, at an air temperature (Ta) about 92°F (33°C) together with high humidity (90-100% RH). From that point on, the lightly clad sedentary individuals can survive for 2, 3 or 6 more days, as air temperature continues to rise at rates of 3, 2 or 1 °F /day (1.7,1.1 or 0.6°C/day) respectively, before the individual's body core temperature (Tc) reaches the unsafe 103°F (39.5°C) level. Donning an impermeable escape suit eliminates the evaporative cooling from sweating, causing Tc to rise even more rapidly. At 92°F (33°C) conditions and wearing the escape suit, Tc will reach 103°F (39.5°C) in about 2 hours. If the suit is put on earlier at a cooler interior temperature of 86°F (30°C) the time available before reaching 103°F (39.5°C) increases to 1 - 3 days depending on the rate of rise in ambient air temperature.

15. SUBJECT TERMS

predictive modeling; disabled submarine; DISSUB; thermoregulation

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS USED IN THIS REPORT

%BF	percent body fat
clo	clothing dry thermal resistance
fac	full acclimation to heat
HR	heart rate
HR_{max}	maximum heart rate
HR_{rest}	heart rate at rest
ICDA	USARIEM's Initial Capability Decision Aid
lb_w/lb_dryair	absolute humidity (humidity ratio), concentration of water in air
M	metabolic activity
met	actual metabolism / resting metabolism
PSI	Physiological Strain Index
Pvap	vapor pressure
RH	relative humidity
SR	sweat rate
T_a	air temperature
T_c	core body temperature
T_{dp}	dew point temperature
T_{mu}	body muscle
Torr	Torricelli unit of pressure (mmHg)
T_{sk}	skin temperature
uac	un-acclimated to heat
Veff	effective air volume per person

DEDICATION

This work is dedicated to the memory of Dr. Wayne G. Horn (1947-2013), Medical Director, Naval Submarine Medical Research Laboratory (NSMRL). Without his support and guidance this work would not have been possible.

ACKNOWLEDGEMENT

We would also like to thank Dr. Reed Hoyt, (USARIEM), Ms. Sandra Wagner, (NSMRL), and Dr. David Fothergill, (NSMRL) for reviewing and editorial assistance. This work was supported by the Naval Sea Systems Command, NAVSEA OOCM, Supervisor of Salvage and Diving, Work Unit Number 50704 and the US Army Medical Research and Materiel Command (MRMC), Military Operational Medicine Research Program (MOMRP).

EXECUTIVE SUMMARY

Sailor's thermo-physiological responses to the unrelenting heat accumulation possibilities of a disabled submarine were simulated with USARIEM thermoregulatory models. The objective of this analysis was to estimate the probable time and interior environmental conditions (air temperature and humidity) when heat related illnesses begin to occur, and the time available for successful rescue of the individuals after they put on escape suits. The modeling indicates a sedentary lightly clad sailor, waiting for rescue, would begin to experience thermo-regulatory failure, i.e., a rapid rise in body temperature, at an air temperature (T_a) about 92°F (33°C) together with high humidity (90-100% RH). From that point on, the lightly clad sedentary individuals can survive for 2, 3 or 6 more days, as air temperature continues to rise at rates of 3, 2 or 1 °F /day (1.7,1.1 or 0.6°C/day) respectively, before the individual's body core temperature (T_c) reaches the unsafe 103°F (39.5°C) level. Donning an impermeable escape suit eliminates the evaporative cooling from sweating, causing T_c to rise even more rapidly. At 92°F (33°C) conditions and wearing the escape suit, T_c will reach 103°F (39.5°C) in about 2 hours. If the suit is put on earlier at a cooler interior temperature of 86°F (30°C) the time available before reaching 103°F (39.5°C) increases to 1 - 3 days depending on the rate of rise in ambient air temperature. Further, knowing cabin air temperature and humidity enables estimates to be made:1) for the beginning of Tc thermoregulatory failure, and 2) of T_c levels of 101.4°F [38.5°C], 103°F [39.5°C], and 105°F [40.5°C]) (Figure 15).

INTRODUCTION

U.S Navy submarines rarely become disabled. The first disablement and loss occurred in 1914 when leaking battery acid in USS F-4 corroded hull rivets that caused progressive flooding, chlorine off gassing, loss of depth control and eventual catastrophic hull failure. Then, after another accident in 1927 when the U.S. Submarine S-4 became disabled and was lost with all hands, rescue procedure planning, equipment and training have continuously been undergoing improvement. As a result, 12 years later, in 1939 off the shore of Portsmouth, N.H. Sailors were successfully rescued from the USS Squalus, which quickly sank after a rear compartment flooded (Stewart, 2008). The disabled Squalus was located on the sea floor at a depth of 240 ft in 29°F (-1.7°C) water, a rescue ship with a diving chamber came to the site and the 33 crew in the non-flooded compartments were transferred to the surface within 40 hours via 4 trips of the diving chamber. A major thermal hazard in such a disabling has been the threat of hypothermia from the environment caused by cold ocean water while waiting the sub's rescue (Castellani et al., 2005).

In recent years, the operations in warm sea water locations and evolving submarine designs have increased the possibility of rising interior air temperatures in a disabled submarine with the threat of sailors developing hyperthermia and related heat illnesses. Simulated disabling tests performed with the USS Dallas near Groton, CT in 2004 and USS Salt Lake City off the San Diego coast in 2006 found that the interior air temperature and humidity slowly but consistently increased (Horn and Daniel, 2007). While disabled, the USS Salt Lake City's interior temperature rose from 72 to 85°F (22 to 29°C) and the humidity rose from 50 to 85% RH over 4 days.

In the present analysis, sailor's thermo-physiological responses were simulated with USARIEM thermo-physiological models to predict a sailor's health risks from slowly rising temperature and humidity that may occur in a disabled submarine. The simulated predictions of the sailors' physiological responses could then help guide rescue and planning operations.

METHODS

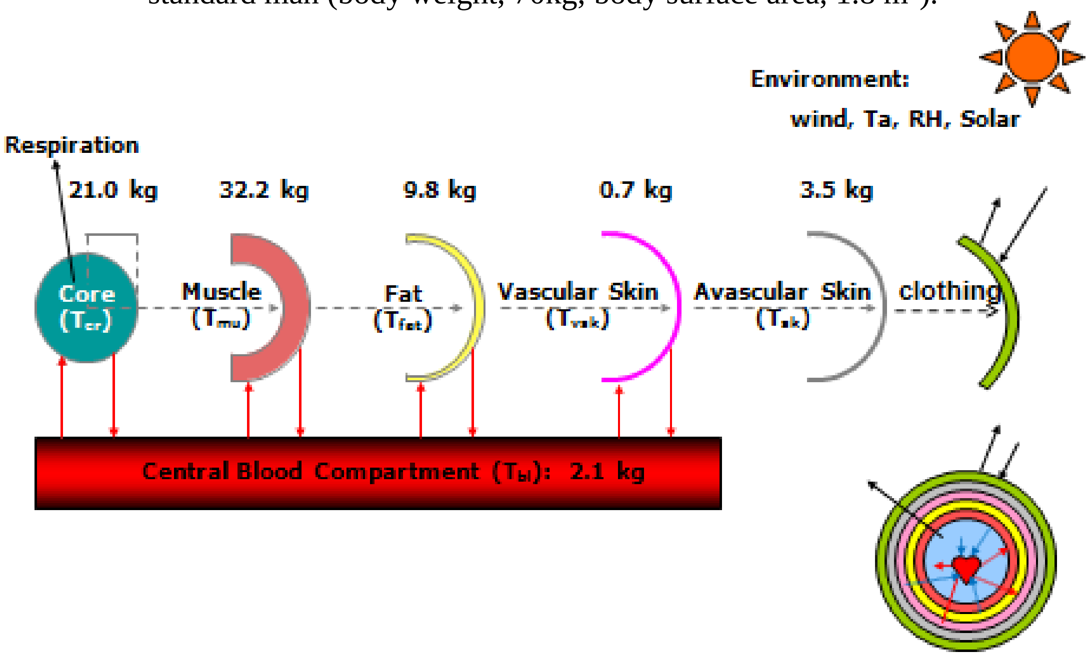
Modeling

The principle model used in the present analysis was SCENARIO (Kraning and Gonzalez, 1997) because it has the most appropriate physiological mechanism features for this application. Also, another related thermoregulatory model, the Initial Capability Decision Aid (ICDA) (Yokota and Berglund, 2006), was customized to estimate the accumulation of water vapor in the air of a disabled submarine during rising temperature situations and correspond to that measured in the tests of the disabled USS Salt Lake City.

SCENARIO_J

SCENARIO_J is the Java language version of the SCENARIO thermo-physiological model developed at USARIEM by Kraning and Gonzalez (1997) (Fig 1). It is a rational human thermoregulation model developed from first principles of physiology, heat transfer and thermodynamics. The physiology and heat transfer principals and properties are based on extensive laboratory experiments from the literature and USARIEM. The main mechanisms for active physiological body temperature control are regulating sweating, shivering and blood flow to the skin. The model accounts for the anthropometrics of height, weight and %body fat. It also accounts for the effects of dehydration and heat acclimation.

Figure 1. Schematics of SCENARIO_J model with compartment arrangements and weights for a standard man (body weight, 70kg; body surface area, 1.8 m^2).



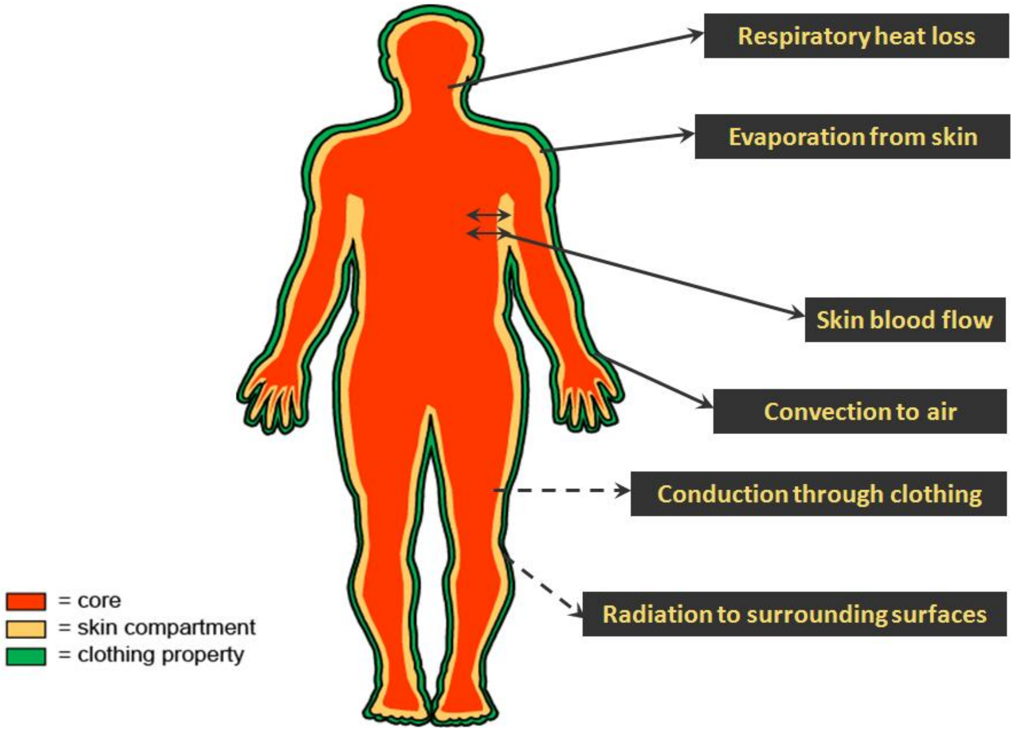
The model represents the human as six lumped parameter tissue compartments (Figure 1), five of which are concentric cylindrical layers representing core, muscle, fat, vascular skin and outer skin. The sixth is the central blood compartment which interacts and exchanges heat directly with all of the compartments except the outer skin. At rest, the core is the principle source of heat. For activity levels above rest, the increased energy is generated in the muscle compartment. With exercise, heat from working muscles predominates and can be more than 10 times that of the core. Heat flows by conduction between adjoining compartments and by convection through blood flow from the central blood compartment. These heat flow pathways help to distribute the heat to the other compartments. The environment exchanges heat and moisture primarily with the skin (through clothing and exposed skin) and also directly with the core through respiration.

SUB_ICDA

The Sub_ICDA model is a version of the USARIEM ICDA model (Yokota and Berglund, 2006) customized for this submarine application. ICDA is an adaptation of Gagge (1971, 1986) model and SCENARIO_J. The ICDA model is similar to SCENARIO_J but simpler with the human represented as two physiological compartments (core and skin).

All of the model's metabolic activity (M) takes place in the core compartment (Figure 2). The customization enables inputting metabolism directly using the met unit to characterize and quantify metabolism (met = actual metabolism/resting metabolism). The model then estimates the heart rate necessary for the metabolism and thermoregulatory cardiovascular responses related to the environment. The sailor's evaporative and respiratory water losses are used to estimate humidity level changes in the occupied submarine environment. Further Sub_ICDA details are available in the Appendix A.

Figure 2. Schematic of Sub_ICDA.



SUBMARINE ENVIRONMENT

The environment of occupied spaces in a disabled submarine can change in different ways depending on the situation and cause of the disablement. This project considers the submarine to be powerless but intact and unable to control temperature, humidity and air motion after being disabled. Further the project considers the temperature of the interior surfaces to approximately equal the occupied space's air temperature. The disablement details are not considered but only the human response to slowly rising temperatures that follow the incident. Also, the primary source of water vapor to increase air humidity is considered to be that from the occupants. The water vapor generated by CO_2 scrubbers adds about 16 g/h per resting sailor and was neglected.

The disablement test of the USS Salt Lake City measured the interior's temperature and humidity for a period of four days following the disabling. The temperature and relative humidity increased rather linearly from 76°F (24.4°C) and 60% RH to 84°F (29°C) and 85%RH during the 4 day test interval. An earlier disabling test on the USS Dallas found a similar temperature rise over a 3 day interval, though the humidity rise was slower and less linear (Figure 3) (Horn and Daniel, 2007).

The SCENARIO_J model needs temperature and humidity as inputs. It is assumed that the temperature in disabled subs will rise approximately linearly as the test measurements of Figure 3 indicate. Further, it is likely that the temperature will eventually become asymptotic to some upper limit when the vehicle reaches a quasi-steady energy balance state depending on the conditions of the sub, its crew and the temperature of the surrounding seawater. At present, the upper level temperature limit mechanisms are undefined and unpredictable. Instead, the interior temperature is assumed to rise

Figure 3. Measured temperature and humidity of occupied spaces in disabled submarines.

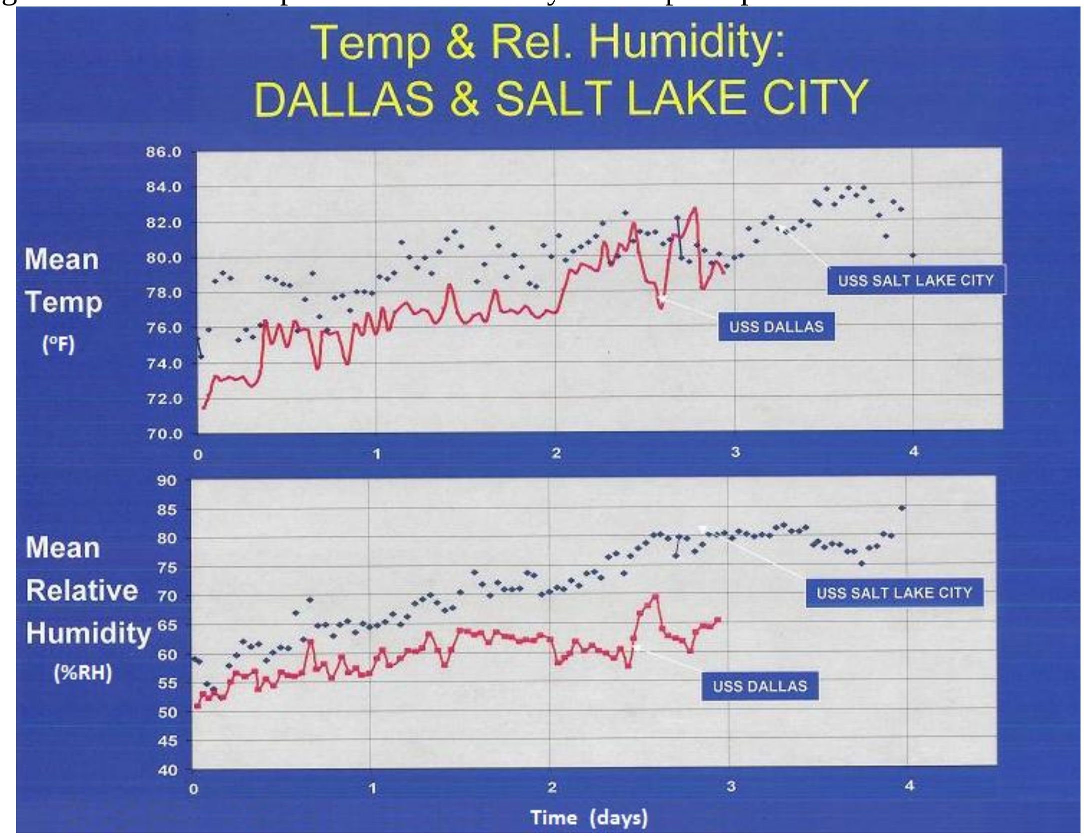


Figure from Horn and Daniel, (2007)

steadily without an upper limit from the pre-disablement temperature. The humidity may also rise. Humidity was predicted with the Sub_ICDA model for different rates of temperature rise, assuming the water vapor in the air increases only from respiration, evaporated sweat and water diffusion through the skin. In turn, water in the air can be absorbed by fabrics, wood and various surface materials. To model the humidity rise for various situations, an effective air volume (Veff) or air mass per person was determined by trial and error to correspond to the humidity rise observed in the disabled USS Salt Lake City. This effective air volume could then be used to predict the humidity behavior for other rates of temperature rise and starting points. Some of the trial and error results are displayed in Figure 4 for the 2°F (1.11°C)/day rise from 76°F (24.4°C) and 60 % RH to find the Veff that results in model predicted RH levels that correspond with those measured in the disabled USS Salt Lake City.

This effective volume of 360 m^3/person was used by Sub_ICDA to determine the humidity behavior for other rates of temperature rise and starting points. The effective volume is larger than the actual air volume per sailor because it agrees with the disabled submarine test measurements and thereby also accounts for unknown adsorption and condensation mechanisms. Results for rates of 1, 2 and 3 °F /day (0.56, 1.11, and 1.67 °C/day) starting from 76°F (24.4°C) are plotted in Figures 5a and 5b. The relative humidity responses with time (Figure 5a) are very similar for the 1, 2 and 3°F/day rates of air temperature rise; reaching 100% in about 6 days. However the absolute humidity (Figure 5a) or water vapor concentration levels in the air (lb_w/lb_dryair) continues to rise after the relative humidity reaches 100% because the temperature continues to increase, allowing the air to absorb more water vapor. The relative humidity and time results of Figure 5a are used by SCENARIO_J to predict the thermoregulatory responses of sailors to these conditions. Figure 5b indicates how the dew point (T_{dp}) of water vapor in the air increases until it reaches air temperature and then increases with T_a.

Figure 4. Results of trial and error method to estimate effective air volume (Veff) per person. Simulated (solid lines) and measured (dotted line) relative humidity in disabled submarine USS Salt Lake City with 2°F (1.2°C)/day temperature rise from 76°F(24.4°C).

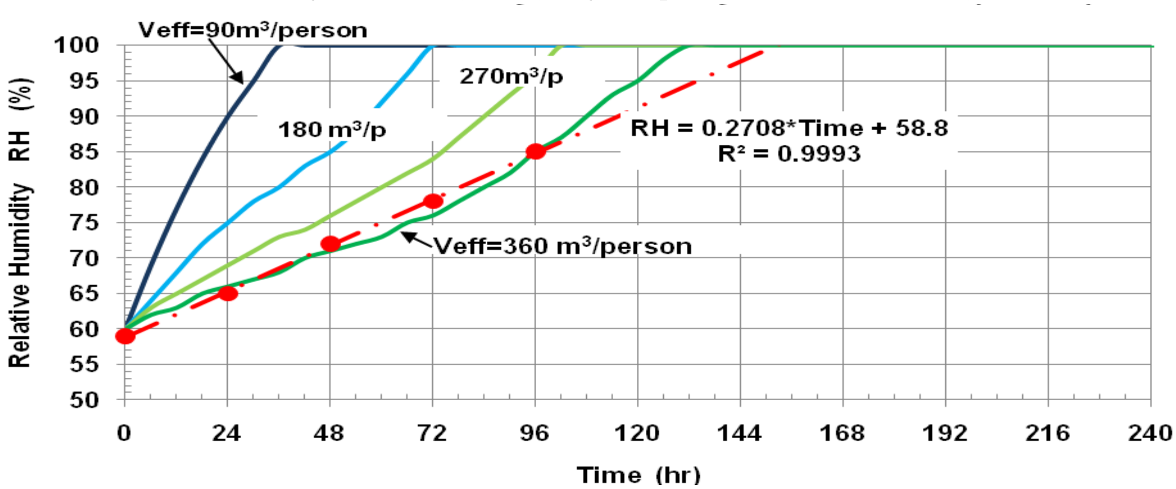


Figure 5a. The relative humidity(RH) and absolute humidity or water concentration in the air generated by sailors(Hughes and Horn, 2006) resting in shorts and T-shirts in a disabled submarine with air temperature increasing at different rates starting from 76°F(24.4°C) and 60% RH.

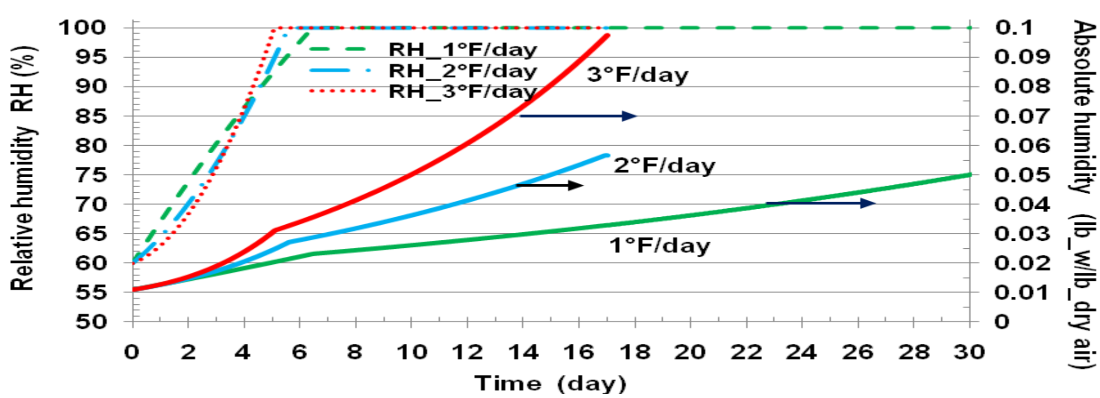
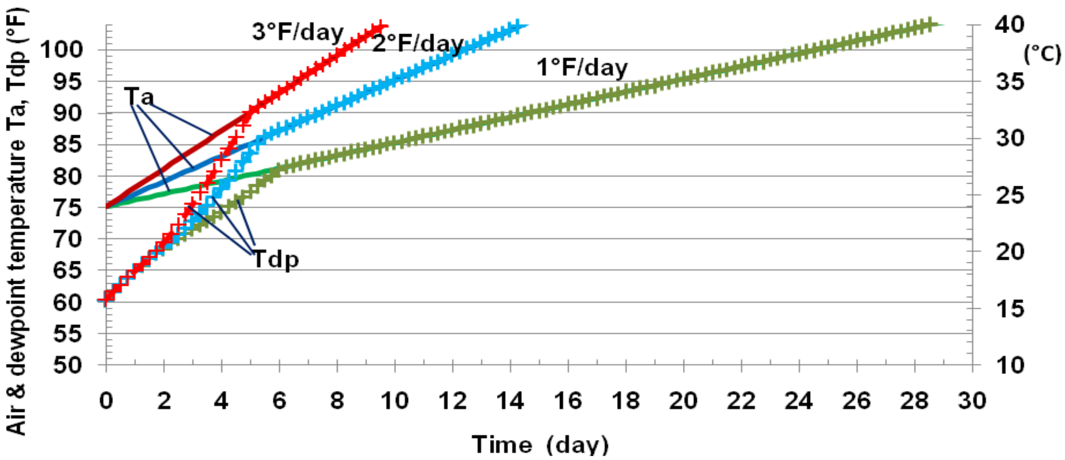


Figure 5b. Dew point temperatures (T_{dp}) resulting from sailors resting in shorts and T-shirts in a disabled submarine with air temperature (T_a) increasing at different rates starting from 76°F (24.4°C) and 60% RH.



PHYSIOLOGICAL ASSESSMENT

Core temperature (T_c), skin temperature (T_{sk}), sweat rate (SR), and heart rate (HR), are predicted by the models in response to the environment, clothing, activity and time and indicate the physiological state of the individual. In addition, the physiological strain index (PSI) (Moran et al.,1998) is also evaluated to assess thermal and cardiovascular strain and the potential for heat illness based on the ratio of deviations in Tc and HR from resting thermally neutral levels to the maximum deviations acceptable for the individual, where:

$$PSI = 5[(HR-HRrest)/(HR_{max}-HR_{rest})] + 5[(T_c-T_c\_rest)/(Tc_{max}-T_c\_rest)]$$

HR_{max} is the maximum heart rate for the person's age (HR_{max} = 220 - age); Tc_{max} = 39.5°C, used in these simulations, is the level where the incidence of heat illness is likely to occur in 50% or more of males (Sawka et al., 2001); T_c_rest = 36.9°C, corresponds to the core temperature of persons at rest in a thermally neutral environment that requires no thermoregulatory activity. HRrest =70 bpm is the rate at rest in a thermally neutral environment used in these simulations, together with an age of 23 yr. Thus PSI is 10 when T_c and HR equal maximum levels. The physiological strain scale between 0 and 10 generally corresponds to a categorical scale from: None/slight to Low, Moderate, High, and Very High as in Fig 6f. PSI levels above 8 represent very high strain states and are to be avoided except for short intervals.

HEAT ACCLIMATION

The effect of heat acclimation on sailor responses to conditions (Fig 6a) in the disabled USS Salt Lake City as estimated by SCENARIO_J, are displayed in Figures 6b, c, d, e and f The graphs indicate that full heat acclimation (fac) is beneficial in reducing heat strain initially. However, in the region where core temperature (Fig 6b) starts to rise rapidly as thermoregulatory failure begins and beyond, there is little difference in modeled responses between acclimated and un-acclimated (uac) sailors.

Figure 6a. Ambient conditions in submarine modeled after measuremets from disabled USS Salt Lake City.

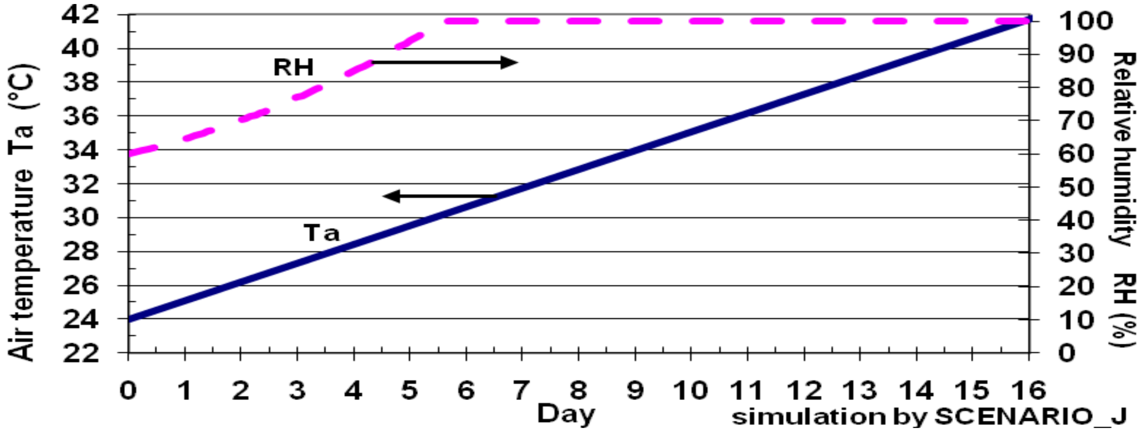


Figure 6b. Core temperature response to conditions of Fig 6a for resting heat un- acclimated (uac) and acclimated (fac) 50th percentile sailors.

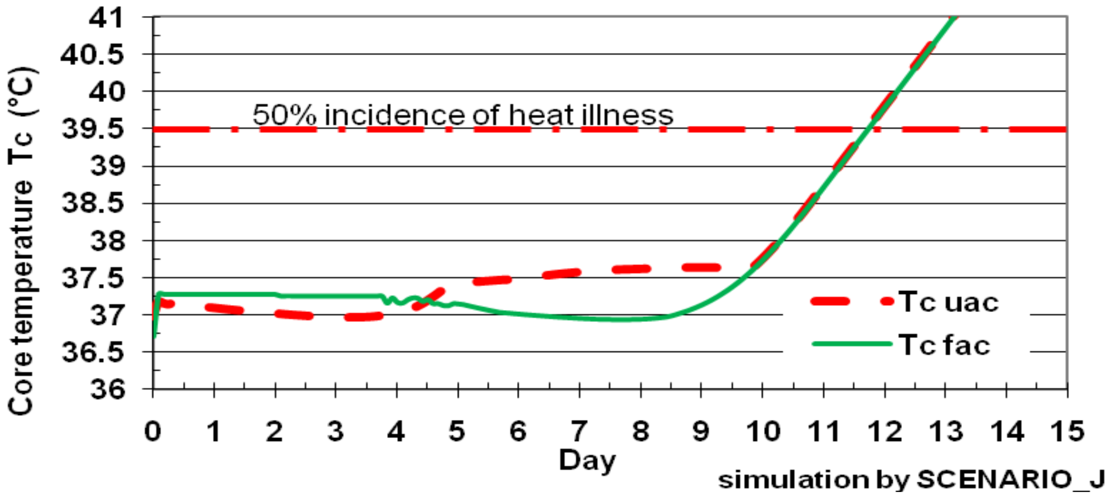


Figure 6c. Skin temperature response to conditions of Fig 6a.

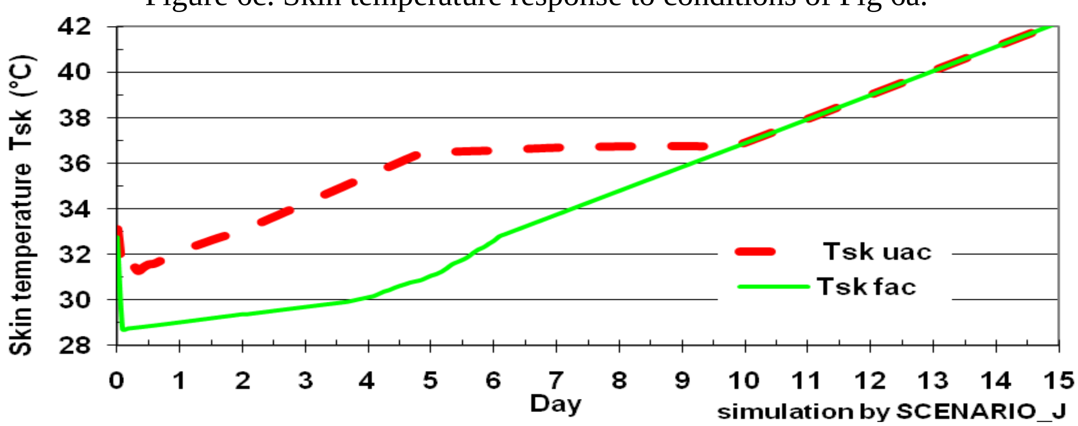


Figure 6d. Heart rate response to conditions of Fig 6a.

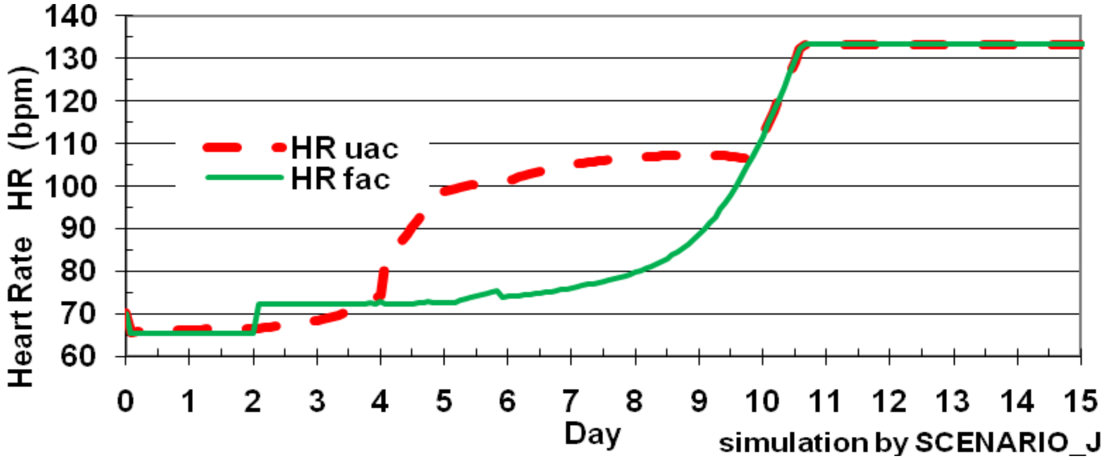


Figure 6e. Sweat rate responses of resting un-acclimated(uac) and fully acclimated (fac) 50th percentile male sailors during conditions of Fig 6a.

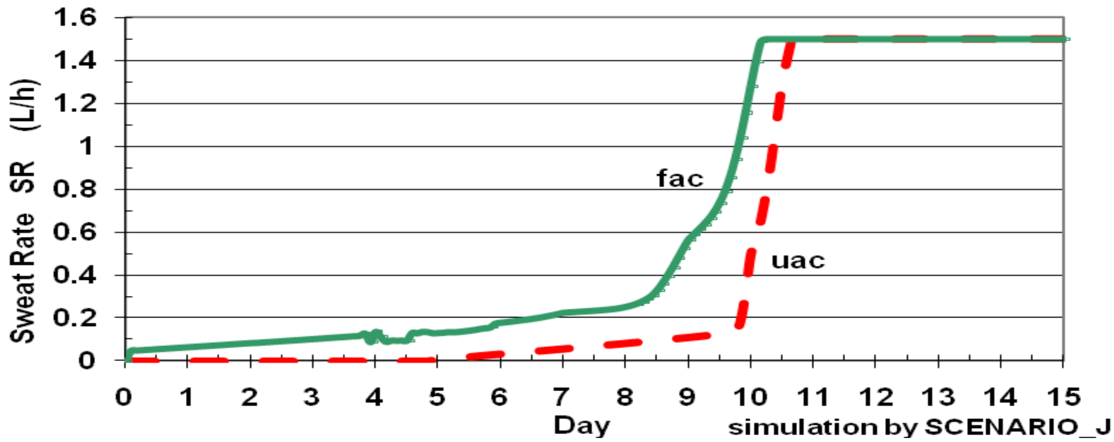
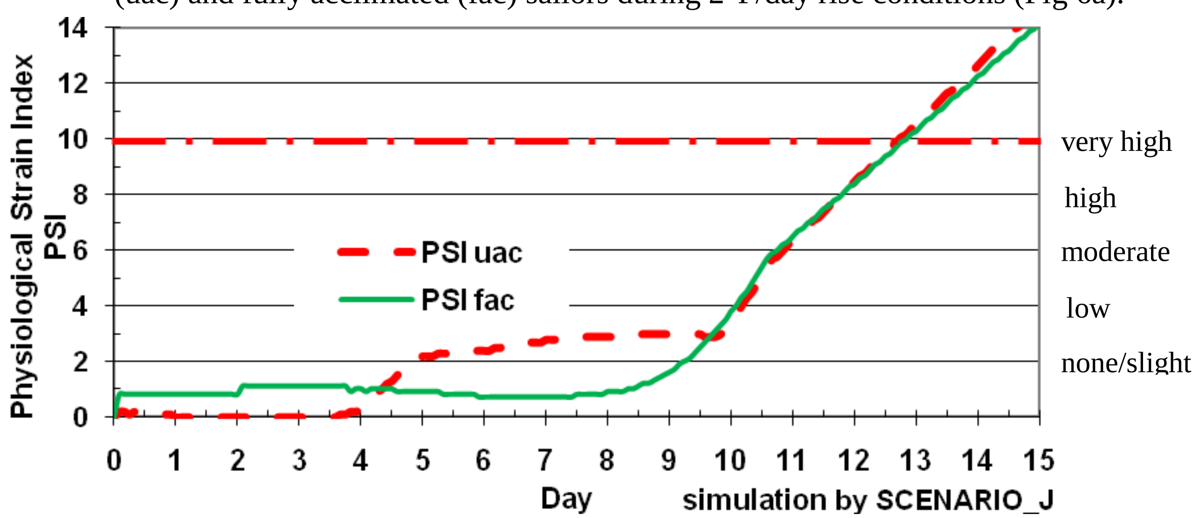


Figure 6f. Heat acclimation effects on the physiological strain index for resting un- acclimated (uac) and fully acclimated (fac) sailors during 2°F/day rise conditions (Fig 6a).



INDIVIDUAL VARIABILITY – Body Size Effects

The U.S. Navy consists of individuals with diverse body sizes and composition (Table 1) (Hughes and Horn, 2006) (Yokota, 2011) and, consequently, the physiological responses of individuals within the Navy populations may differ from average responses. Assessing the thermal responses of different individuals is important for rescue purposes and to create safety guidelines for military populations. Submariners live for long periods in constant comfortable conditions and are unlikely to be heat acclimated or to retain it. Further as figures 6b-f indicate acclimatization has little effect once thermoregulation begins to fail. Thus, this study examined the effects of body size and composition on un-acclimated (uac) sailors.

Table1. US Navy Percentile Anthropometric Summary

percentile	5th	50th	95th
Height - inch (cm)	64.7 (164.3)	69.4 (176.3)	74.6 (190)
Weight - lb (kg)	133.4 (60.5)	178.6 (81)	227.3 (103.1)
Body fat - %	9.81	16.9	24

The effects of these anthropometrics on thermo-physiological responses were estimated by SCENARIO_J for the 5th, 50th and 95th percentile sailor experiencing the conditions (Fig 6a) of the disabled USS Salt Lake City. The results are displayed in Figures 7a-e.

The core temperature (Fig 7a) and PSI (Fig 7e) responses indicate that the smaller (5th percentile) sailors can maintain a reasonable steady body temperature longer in the rising heat than the bigger (95th percentile) sailors. The difference is about a day for a compartment temperature rising at 2°F/day which may be useful in designating the order of escape to reduce possible heat illness and its effects on egress. The results also illustrates that individual water loss (sweat rate, Fig 7d), and the need to replace it, progresses slowly until about the 8th day and the beginning of a rapid increase in body temperature when T_a is about 33°C (91°F). This sweat rate versus time or air temperature response patterns may suggest the rate of water distribution to the crew if the water supply is limited.

Figure 7a. Core temperature responses of un-heat acclimated 5th, 50th and 95th percentile sailors experiencing conditions in disabled submarine while at rest in shorts and T-shirts.

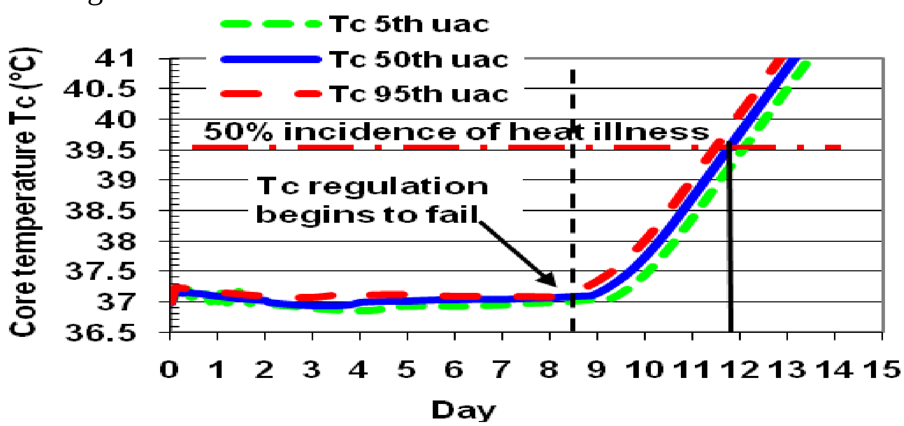


Figure 7b. Simulated skin temperatures of resting 5th, 50th and 95th percentile sailors in disabled submarine while at rest in shorts.

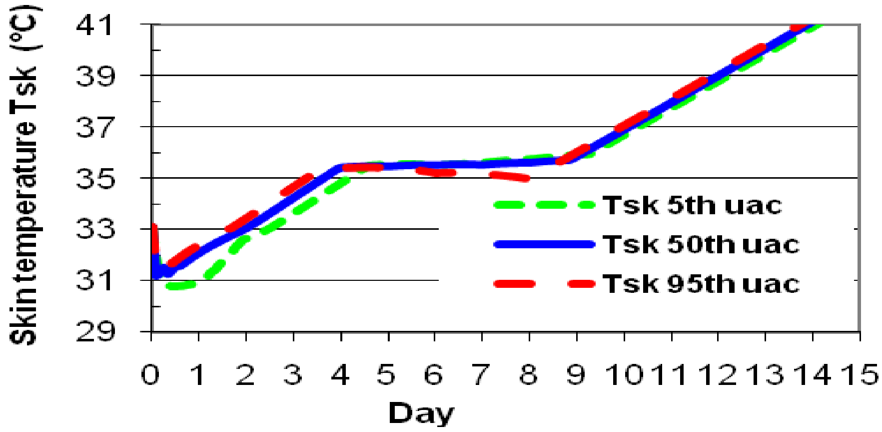


Figure 7c. Heart rate responses of 5th, 50th and 95th percentile sailors experiencing conditions of the disabled submarine while at rest in shorts and T-shirts.

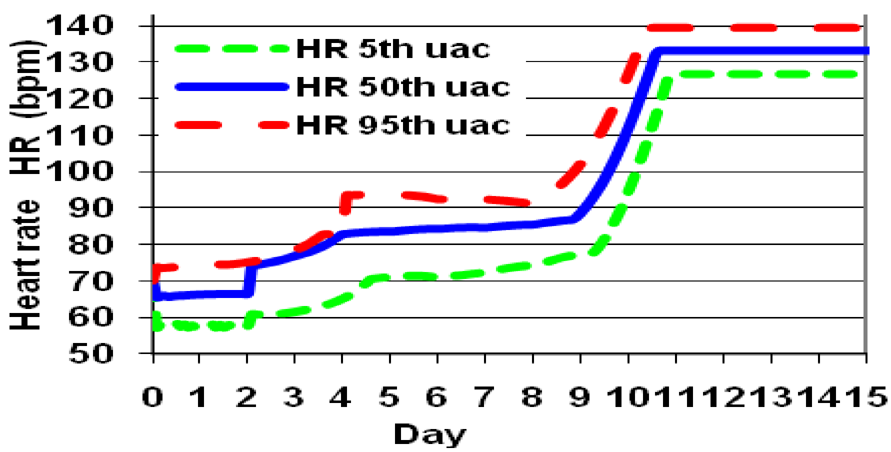


Figure 7d. Sweat rates of the anthropometric 5th, 50th and 95th percentile sailors at rest in simulated disabled USS Salt Lake City.

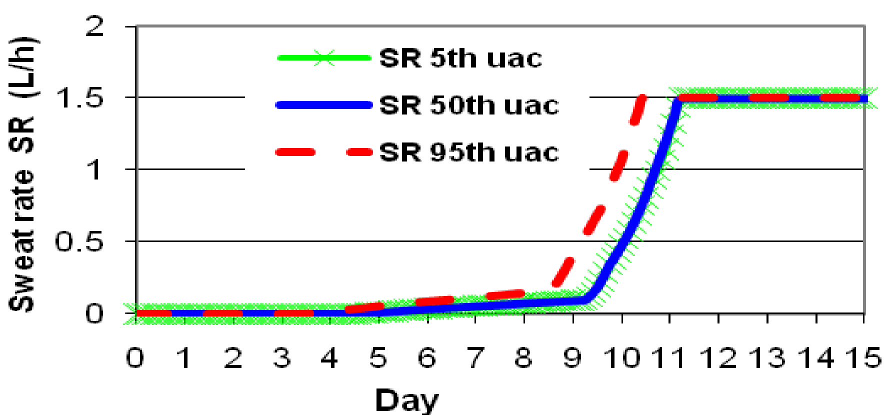
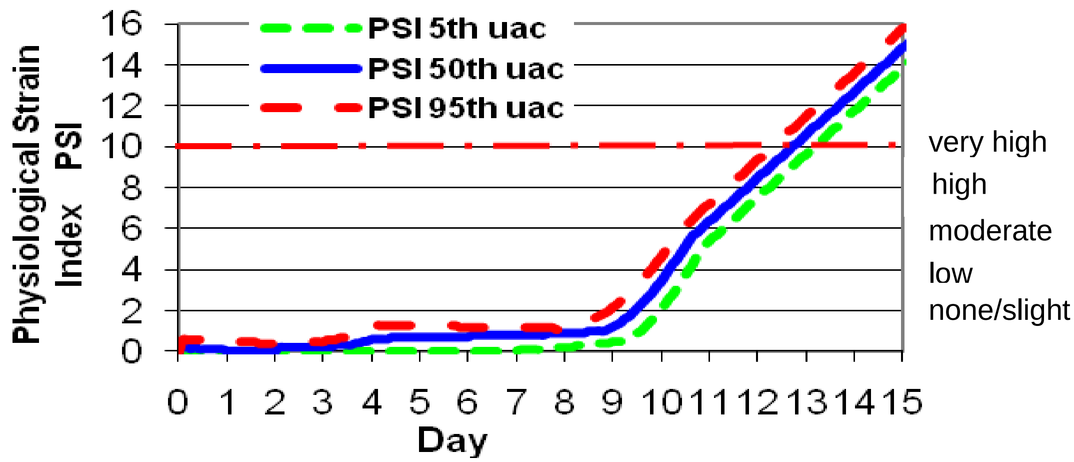


Figure 7e. Predicted physiological strain levels of 5th, 50th and 95th percentile sailors



RESULTS

THE EFFECTS OF RATE OF TEMPERATURE RISE ON PHYSIOLOGY

Depending on the nature of the disablement, the submarine's design, level of occupancy, the water conditions and location, the rate of inside T_a rise may differ from the 2°F (1.11°C)/day rate measured in the disabled USS Salt Lake City tests. The rate of temperature rise after disablement, its cause and any upper temperature limit information or estimates could influence the urgency and planning of the crew's rescue. Further, the humidity changes inside also affect sailor heat strain and can be affected by furnishings, activities and the type of disablement. Figures 8a and 8b indicate environmental input conditions for the SCENARIO_J model, and Figures 8c to 8e presents comparisons of the physiological responses of un-acclimated sailors of medium build (e.g., height: 176 cm; weight: 81kg; percent body fat (%BF): 17%, [Hughes and Horn, 2006])) to these environmental conditions with 3 different rates of temperature rise (i.e., 1, 2 and 3°F/day (0.56, 1.11 and 1.67°C/day)) starting from 75.2°F (24°C) and 60% RH (Figure 8a&b). The relative humidity and water vapor pressure (Pvap) levels in the air (Figure 8b) are assumed to be driven by water vapor releases from the sailors and modeled to correspond to the test results from the USS Salt Lake City.

The relative humidity increases with time are very similar for the 1, 2 and 3°F/day rates of T_a rise; reaching 100% in about 6 days. However, vapor pressure continues to increase though saturated (100% RH) because the saturated vapor pressure of water increases with temperature enabling the air to absorb more water vapor. The increasing Pvap reduces the vapor pressure difference between with water on the skin and the environment, reducing the evaporation rate per unit area of water on the skin and causing the sweat wetted area to increase. Eventually the skin is nearly completely wet, limiting any further evaporative heat loss increase and causing the body temperature to rise more rapidly (Figure 8c).

The sailors at the time of the disablement are wearing standard uniforms of long sleeved shirt and trousers, with an intrinsic resistance to dry heat flow of about 0.61 clo (0.095°Cm^2w^{-1}) between skin and outer surface of the clothing. For comparison, a winter business suit is about 1 clo (0.155°Cm^{2}w$^{-1)}$. Their T_{sk} would be about 91°F (33°C). When T_{sk} increases to about 95°F (35°C), the Sailor will likely feel some warm discomfort and it is assumed they will then change into shorts and T-shirts or similar light attire, reducing their clothing insulation to about 0.2 clo (0.03°C m^{2}w^{-1}) (Fig 8c) . This clothing reduction will occur after about one day with the temperature rising slowly at 1°F (0.56°C)/day, and after about 2 hours for the 2°F (1.11°C)/day and 3°F (1.67°C)/day conditions, but when they choose to reduce their clothing had little effect on final results.

Figure 8a. Air temperatures input for SCENARIO_J simulations of medium-built sailor in a disabled submarine with different rates of slow continuously increasing T_a.

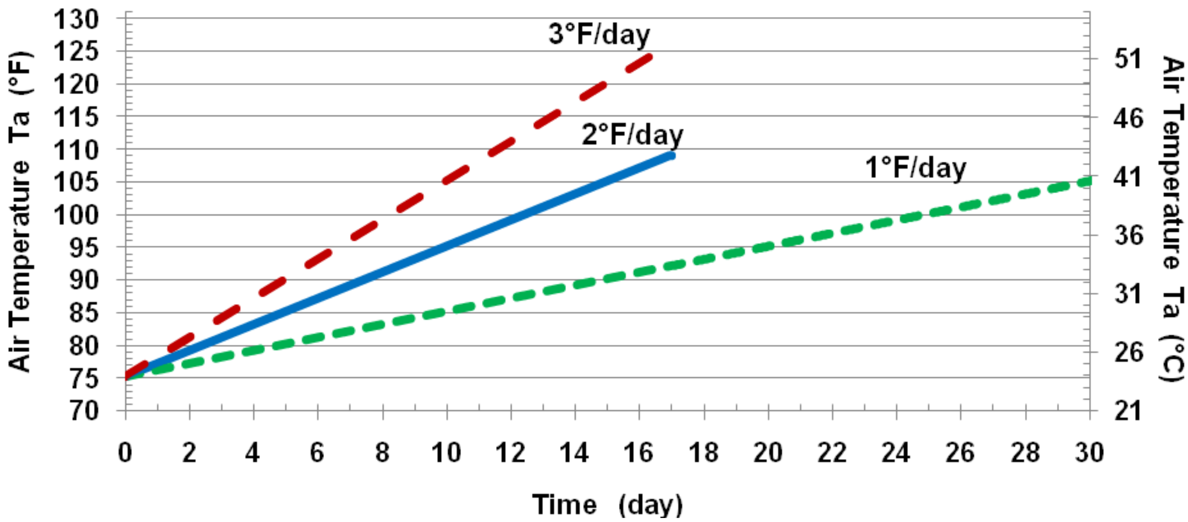


Figure 8b. Relative humidity and water vapor pressure levels in the air resulting from water vapor releases from sailors in a disabled submarine with slowly increasing T_a. Note Pvap continues to increase after RH reaches 100% because of the rising Ta.

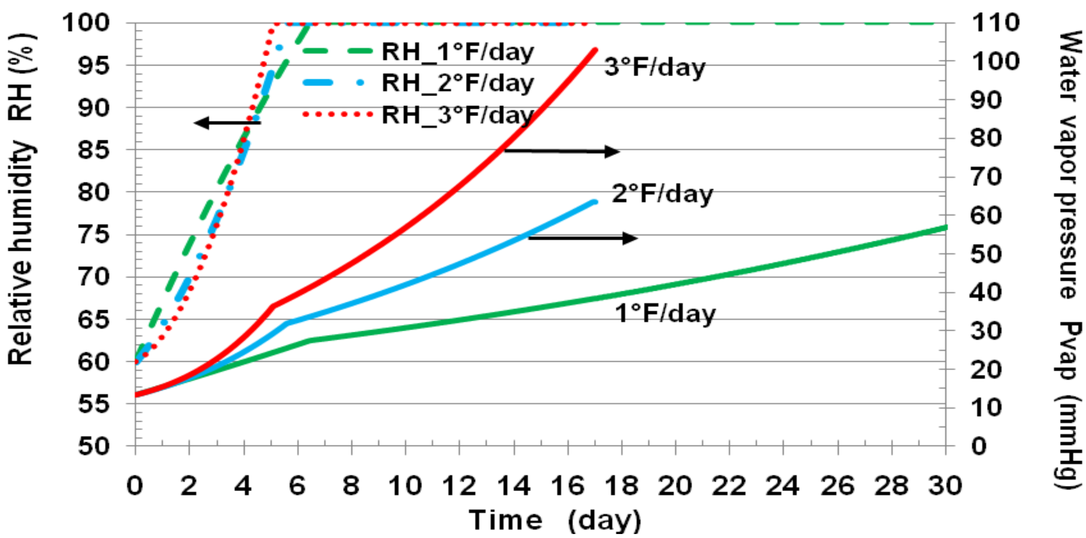


Figure 8c. Core and skin temperature from SCENARIO_J simulations of a resting medium built sailor in a disabled submarine with T_a rising at three different rates, starting from 75°F (24°C) & 60% RH. Initially the sailors are wearing long sleeved shirts and trousers for 24 hours and change into shorts and T-shirt shortly after disablement when T_{sk} reaches about 95°F (35°C).

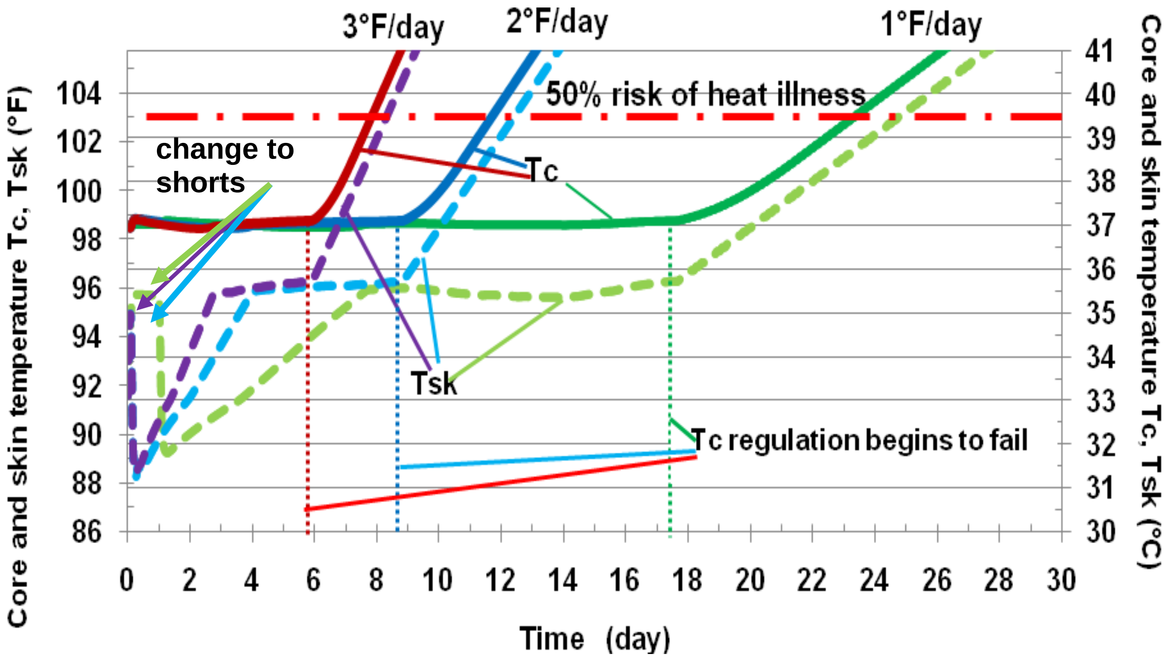
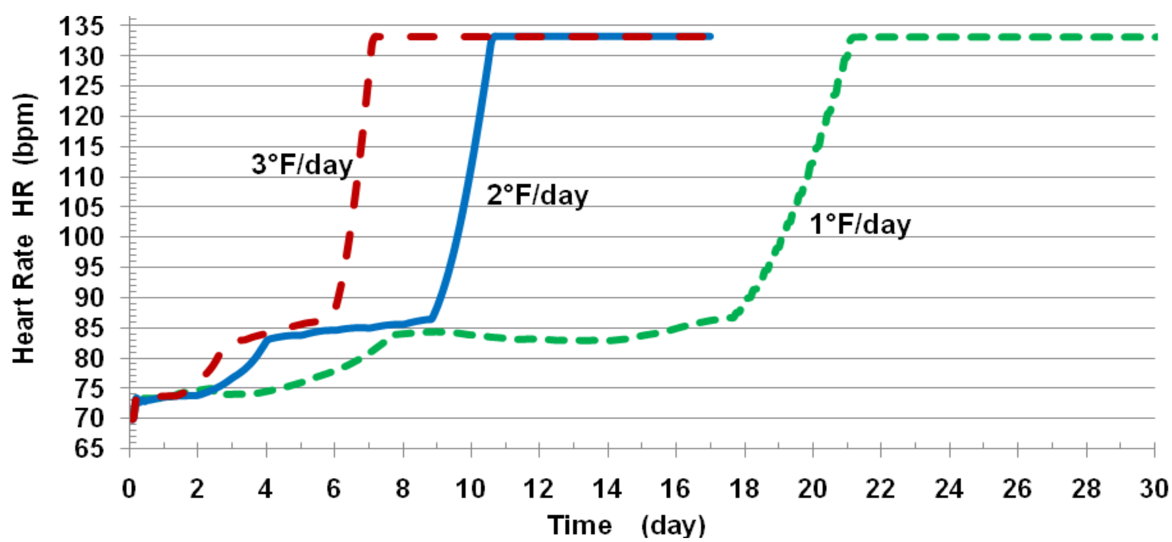


Figure 8d. Heart rate from SCENARIO_J simulations of resting medium built sailors in disabled submarine with T_a rising at three continuous slow rates, starting from 75°F (24°C) & 60% RH and initially wearing long sleeved shirt and trousers but later changing into shorts and T-shirt (Fig 8c).



The heart circulates blood to satisfy metabolic needs and also to cool the core. The sailor is assumed to have a constant resting level of activity but skin blood flow for cooling increases in response to rising T_c and T_{sk} until it reaches its maximum. The HR to deliver this flow is assumed to be maintained at this level as long as the person's hydration level remains normal (Figure 8d).

The sweat rates in Figure 8e increase rapidly after T_c regulation begins to fail because heat loss is insufficient. The hypothalamus correspondingly increases sweating and blood flow to the skin to increase heat loss. But with the continuously rising air temperature and humidity of such situations, an energy balance is now not possible and both sweat output and skin blood flow reach their maximums capabilities without a balance and T_c stability. These high sweat and skin blood flow rates can be maintained until heat illness occurs assuming the sailor's level of hydration is maintained. The T_c and PSI limit results of the Figure 8c and 8f graphs are summarized in Table 2. Observe in Table 2, that the ambient T_a and humidity at the beginning of T_c regulatory failure are all about equal (T_a=92°F & 100%RH) for T_a rise rates of 1, 2 and 3°F/day. Similarly when T_c = 103°F and PSI = 10, the environmental parameters are also equal at 99°F and 100°F respectively with 100% RH. With dehydration sweat rate and blood flow could be reduced resulting in regulatory failure occurring sooner at lower air temperatures.

Figure 8e. Sweat rates from SCENARIO_J simulations of medium built sailors in disabled submarine with T_a rising.

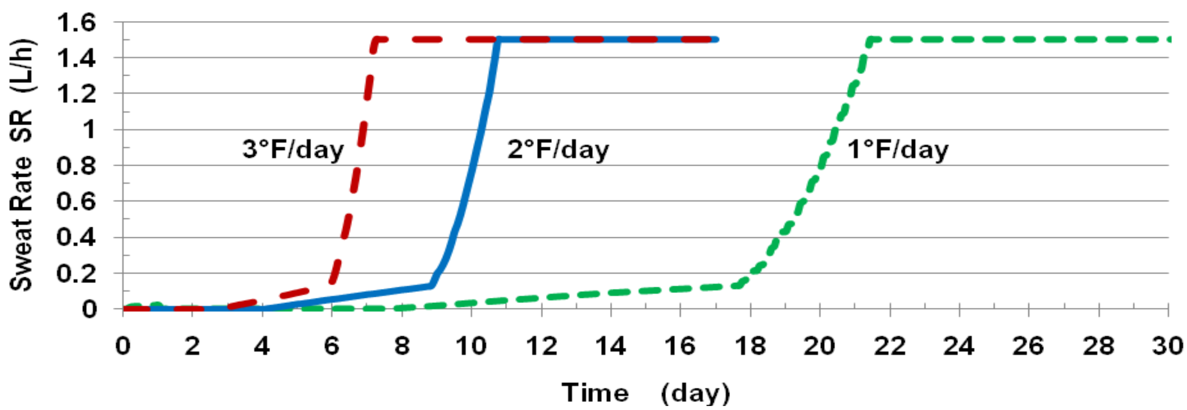


Figure 8f. The physiological strain index (PSI) from SCENARIO_J simulations of resting medium built sailors in disabled submarine with air temperature rising at three continuous slow rates, starting from 75°F (24°C) & 60% RH.

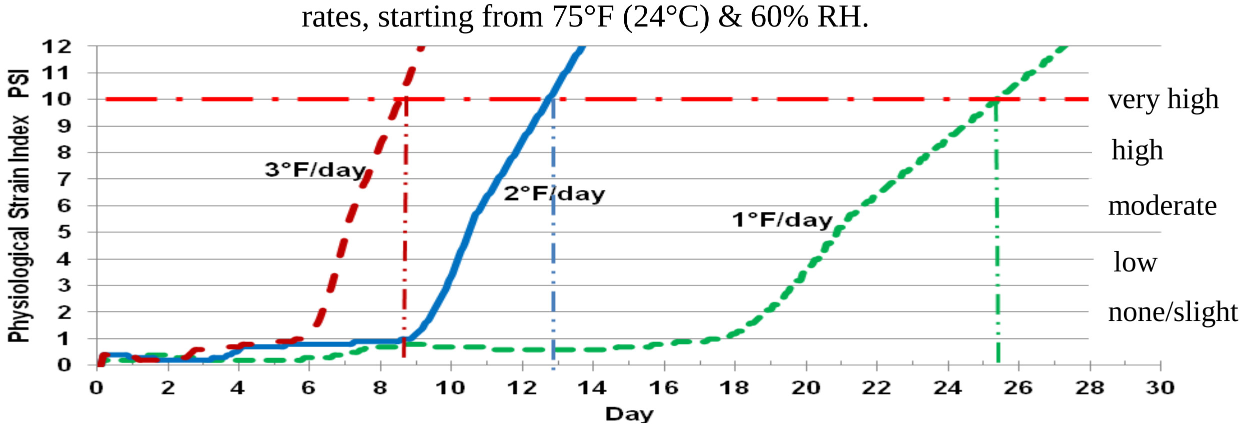


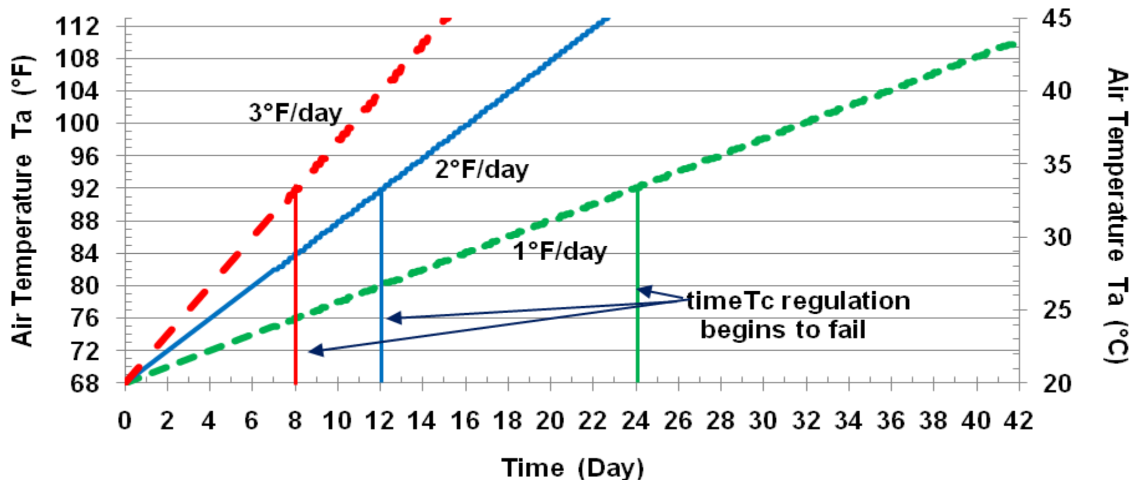
Table 2. Summary of environmental conditions and elapsed time since disablement to when T_c regulation begins to fail, T_c reaches 103°F(39.5°C) and physiological strain index (PSI) reaches 10 starting from environmental conditions of 75°F(24°C) and 60% RH.

Rate of T_a rise		T_c regulation fails			T_c reaches 103°F(39.5°C)			PSI reaches 10		
ΔTa/day		time	Ta	RH	time	Ta	RH	Time	Ta	RH
°F/day	°C/day	day	°F (°C)	%	day	°F(°C)	%	Day	°F(°C)	%
1	0.56	17	92 (33.4)	100	23.5	99 (37)	100	25.3	100 (38)	100
2	1.11	8.5	92 (33.4)	100	11.8	99 (37)	100	12.7	100 (38.1)	100
3	1.67	5.7	92 (33.4)	100	7.8	99 (37)	100	8.5	100 (38.2)	100

EFFECT OF STARTING CONDITIONS

If a planned situation, route or activity increases the possibility of disablement and increasing interior temperatures, the submarine's temperature and humidity could be reduced, lengthening the time available for a successful rescue. For example, Figures 9 a - h show the effect on responses of the medium-built non-heat acclimated sailor to a pre-disablement lowering of cabin conditions from 75(24°C) to 68°F (20°C) with 50%RH. The preparation lengthened the safe rescue window by 40%.

Figure 9a. Air temperatures after disablement starting from pre-disablement conditions of 68°F and 50%RH.



Note, from comparing Figure 9a with Table 2, that the time to the beginning of T_c regulatory failure increases from:

5.7 to 8 days or 1.3 Δdays for a 3°F/day T_a rise rate;
8.5 to 12 days or 3.5 Δdays for a 2°F/day T_a rise rate; and
17 to 24 days or 7 Δdays for a 1°F/day T_a rise rate.

Further, the Δday change for initial temperatures different from 75°F are for a given dT_a/dt are approximately linear with the difference in starting temperatures from 75°F and the Δdays for a 68°F Tstart:

Δdays (for Tstart) = (Δdays)/(75-68) * (75-Tstart), Thus for other starting temperatures before disablement the safe period before thermoregulation begins to fail can be estimated by equation 2 with Table 2 and Figure 10a.

i.e.: Δdays (for Tstart=72°F & 2°F/day) = (3.5)/(75-68))*(75-2) = (3.5/7)*3 = 1.5day

or days until T_c begins to fail after an initial temperature of 75°F with dT_a/dt=2°F/day:

Δdays (for Tstart=72°F & 2°F/day) = 8.5+1.5 = 10days.

Figure 9b. Absolute humidity (also called humidity ratio) levels after disablement, starting from pre-disablement conditions of 68°F and 50%RH.

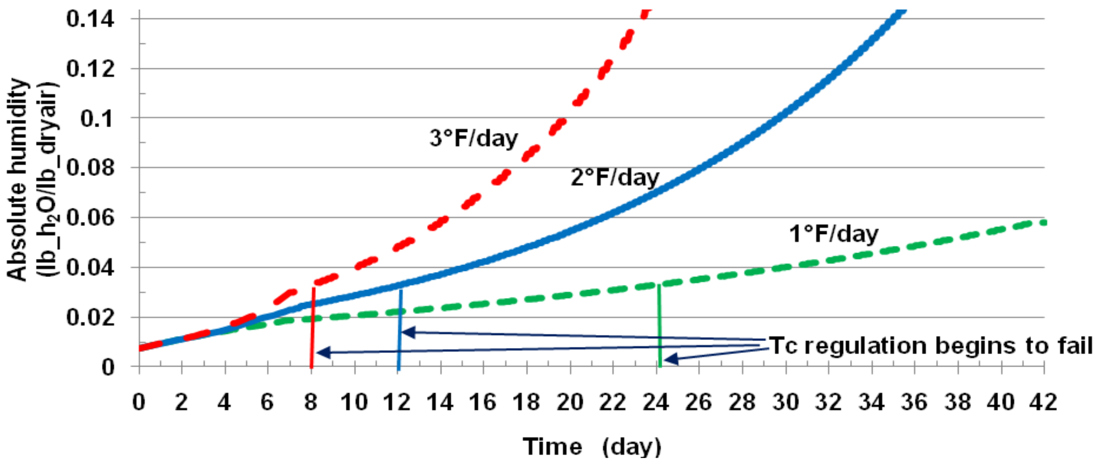


Figure 9c. Relative humidity levels after disablement, starting from pre-disablement conditions of 68°F and 50%RH.

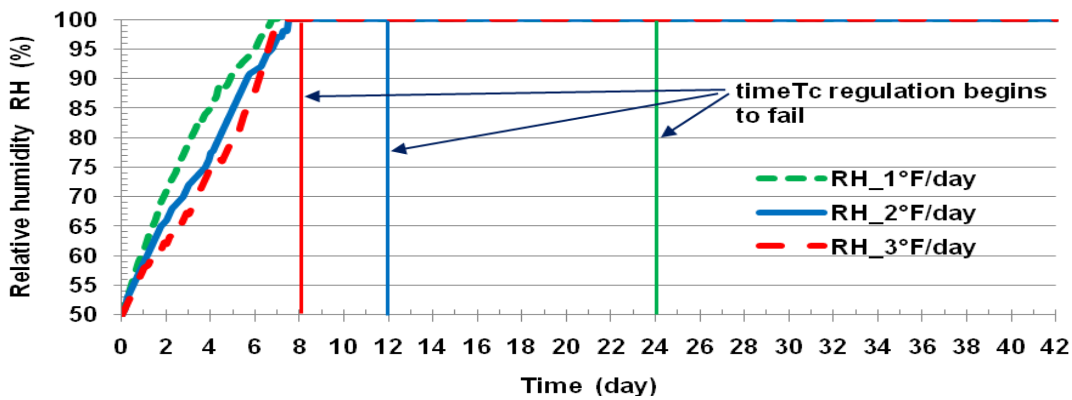
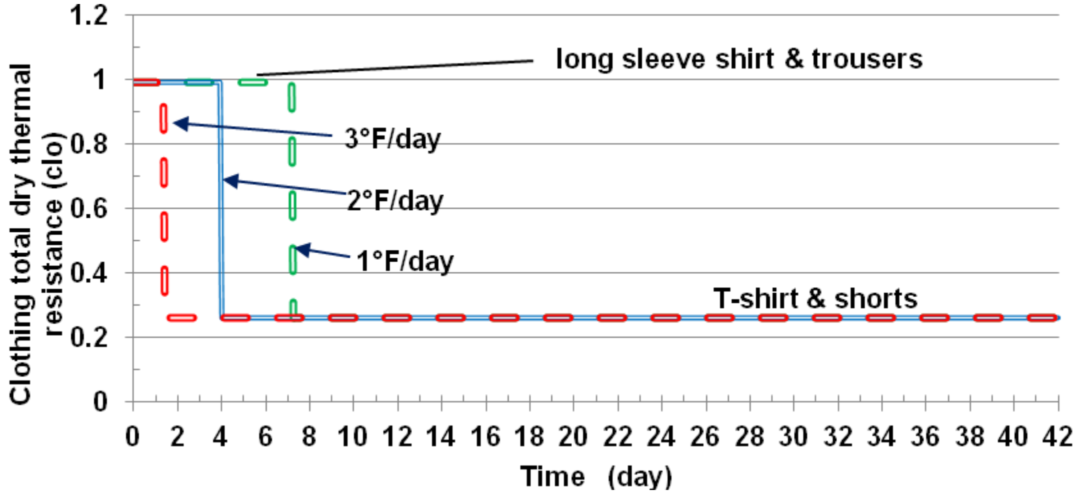
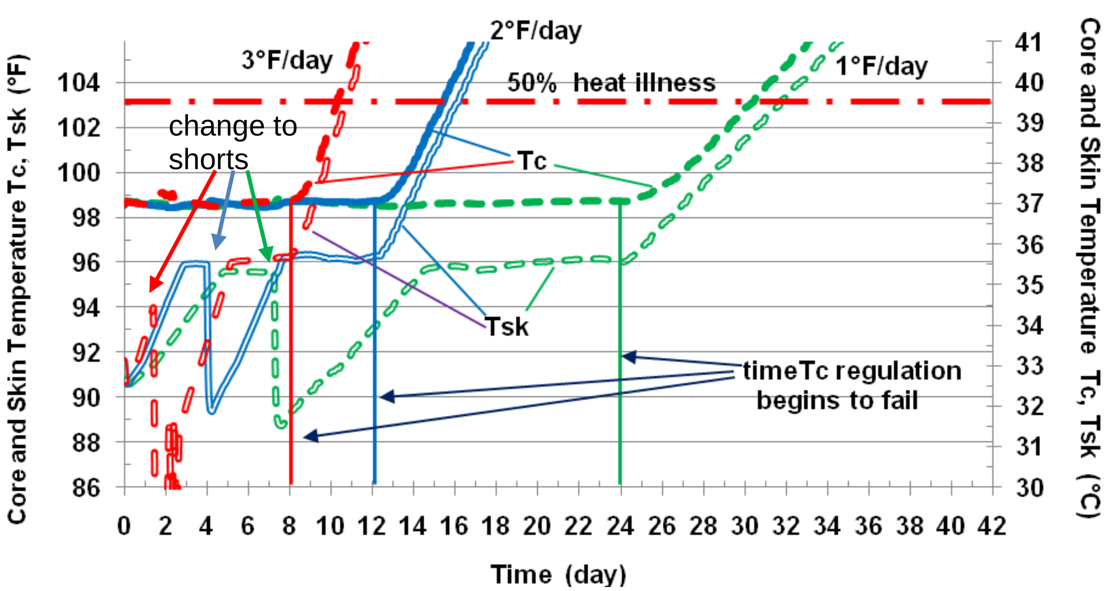


Figure 9d. Clothing insulation changes assumed after disablement to reduce thermal discomfort and T_{sk} with cabin temperatures starting at 68°F (20°C) and increasing steadily at three different rates.



Sailors are initially wearing a long sleeved shirt and trousers or similar. When their T_{sk} reaches about 95ºF, they will feel some warm discomfort and change into lighter attire (shorts and T-shirt) as indicated in Figure 9d, which causes T_{sk} to decrease before rising again in Figure 9e.

Figure 9e. SCENARIO_J simulation of core and skin temperatures for an medium-built sailor in a disabled submarine with air temperature rising from 68°F(20°C)/50% relative humidity (RH) at rates of 1°F/day, 2°F/day and 3°F/day.



The time when T_c begins to rise rapidly as sailor's physiological heat loss mechanisms become insufficient are indicated in Figures 9a and c. Notice that the air temperature and humidity levels for T_c regulatory failure are the same and independent of the rate of temperature rise. These environmental levels are also equal to those indicated in Table 2 and Figure 8 for disablements beginning with higher a T_a of 75°F (24°C) but then change to a cooler 68°F(20°C)

T_a before disablement occurs give 2, 3.5 and 7 days longer time to find and accomplish the rescue.

Figure 9f. SCENARIO_J simulation of heart rate of a medium built sailor in disabled submarine with T_a rising at 3°F/day (1.66°C/day), 2°F/day and 1°F/day, starting from 68°F (20°C)/50%RH and initially wearing long sleeved shirt and trousers and changing into shorts and T-shirt as indicated in Figure 9d.

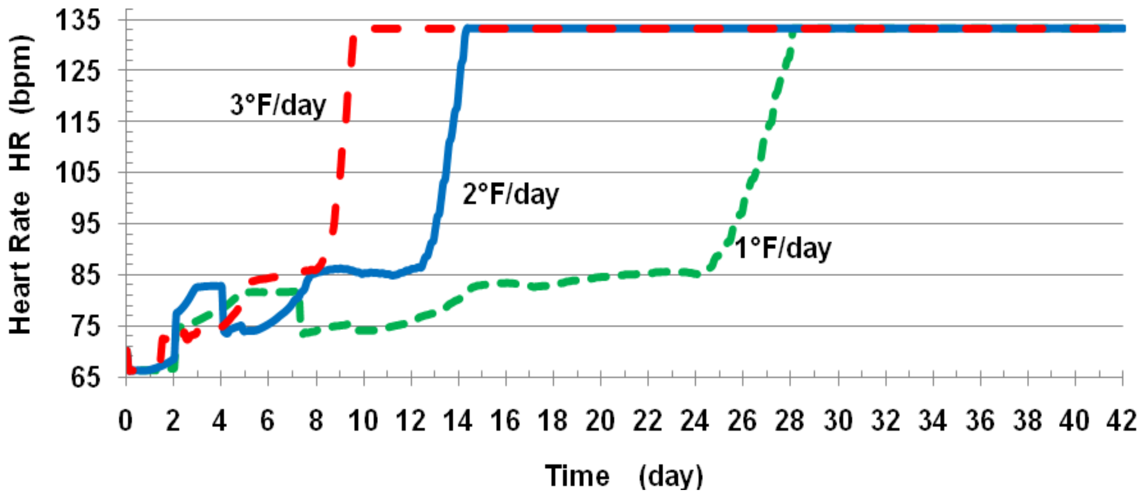


Figure 9g. SCENARIO_J simulation of physiological strain index (PSI) for sailor medium built sailor in disabled submarine with air temperature rising at different constant rates, starting from 68°F (20°C)/50% RH and initially wearing long sleeved shirt and trousers and changing into shorts and T-shirt as indicated in Figure 9d.

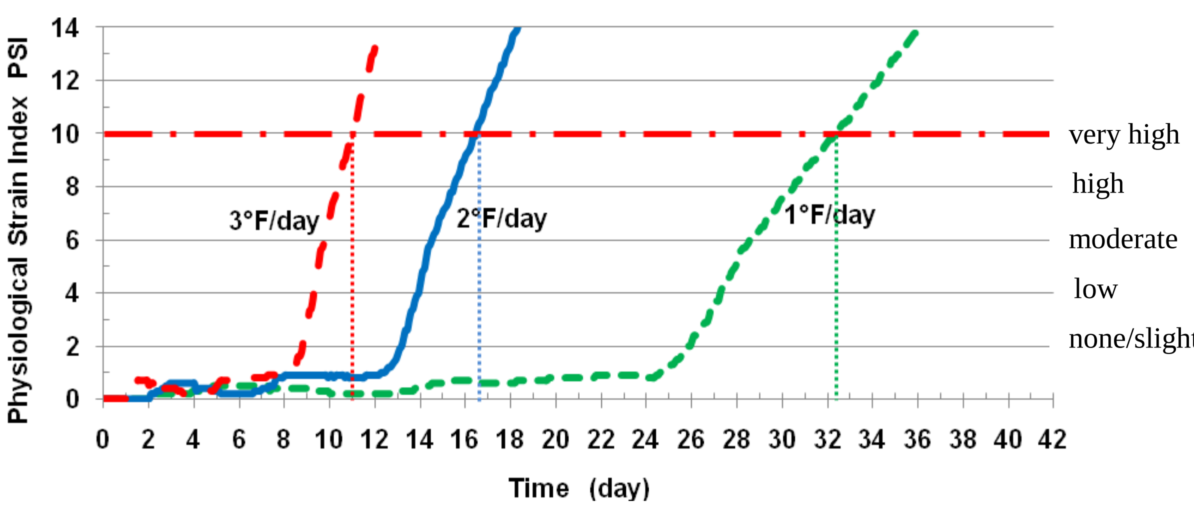
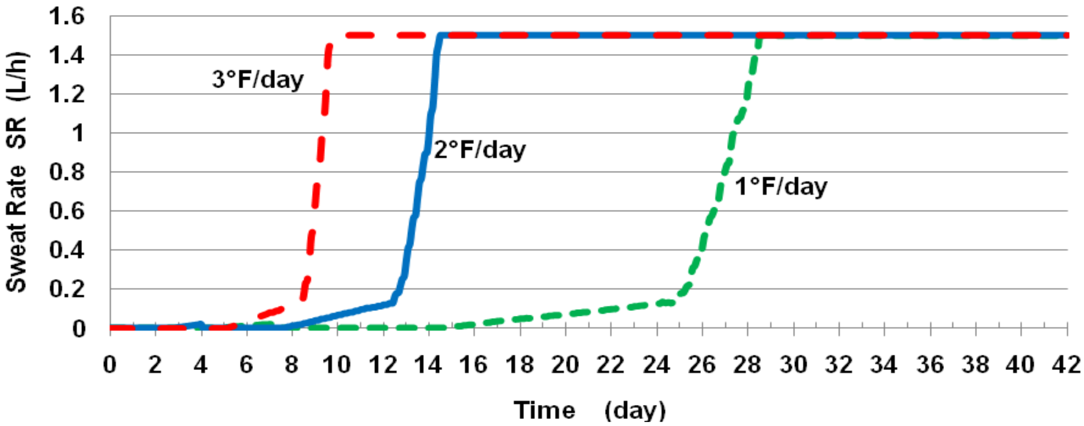


Figure 9h. SCENARIO_J simulation of sweat rate of medium-built sailor in disabled submarine with T_a rising at 3°F/day (1.66°C/day), 2°F/day and 1°F/day, starting from 68°F(20°C)/50% RH and wearing with long sleeved shirt and trousers before changing into shorts and T-shirt as indicated in Figure 9d.



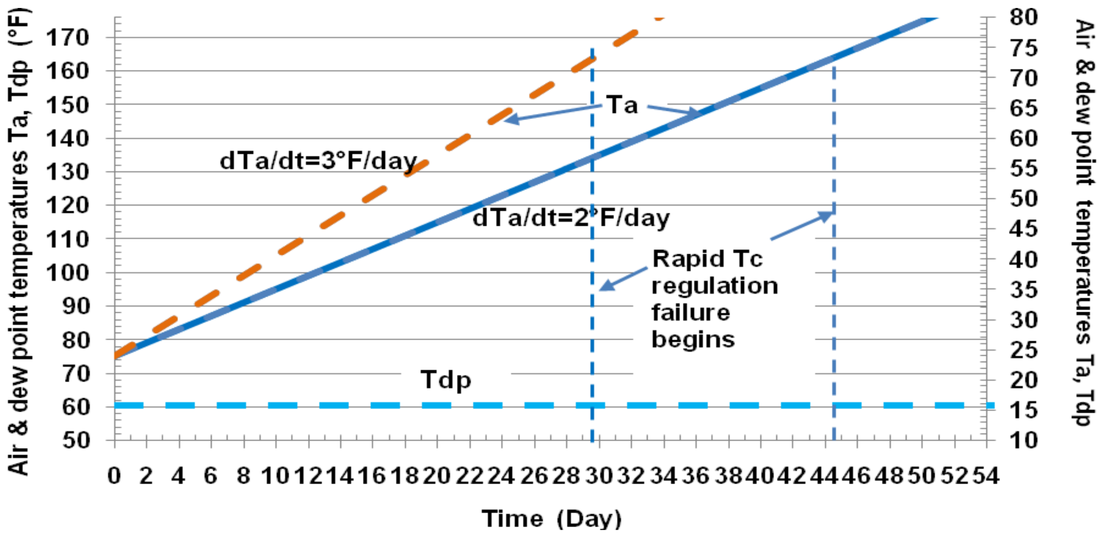
EFFECT OF HUMIDITY

As surrounding air and surfaces become warmer, the human's dry heat loss capabilities decrease and thermoregulation relies increasingly on evaporative heat loss processes from skin and respiratory surfaces. The rate of evaporation depends largely on the vapor pressure difference between water on the evaporating surface and in the surrounding air. Disabled submarine test measurements (Figure 3) and calculations (Figures 4 and 5) indicate the water content of air increases steadily and thus progressively impairs the sailor's evaporative heat loss mechanisms. If water vapor in the air could be removed or controlled by adsorption, condensation or other means, the safe stay time in the disabled submarines would be extended. The following simulations illustrate the rescue time and human response benefits of humidity control efforts characterized by: 1) maintaining constant absolute humidity or T_{dp} temperatures or 2) maintaining constant levels of RH.

1) Maintain Absolute Humidity or Dew Point Temperature at Pre-disabled Level

Sailor responses (medium built, non-acclimated) and environmental conditions for the disabled submarine where absolute humidity can be maintained constant at the initial level are displayed in Figures 10-a-e for initial conditions of 75°F (24°C) and 60%RH. For these conditions the absolute humidity, dew point temperature (T_{dp}) and vapor pressure are 0.0113 lb_H_2O/lb_dry air, 60°F (15.8°C) and 13.7 mmHg (Torr) respectively and held at that level after disablement.

Figure 10a. Disabled submarine with a constant dew point of 60°F(15.8°C) but T_a rising at 3°F/day (1.66°C/day), and 2°F/day (1.11°C/day), starting from 75°F (24°C)/60% RH.



At the time of disablement sailors are wearing long sleeved shirt and trousers but change into T-shirt and shorts as indicated by rapid drop in T_{sk} (Fig 10c).

Figure 10b. Relative humidity and vapor pressure (Pvap) of water in disabled submarine with a constant dew point of 60°F (15.8°C) but T_a rising at 3°F/day (1.66°C/day), and 2°F/day (1.11°C/day), starting from 75°F (24°C)/60% RH.

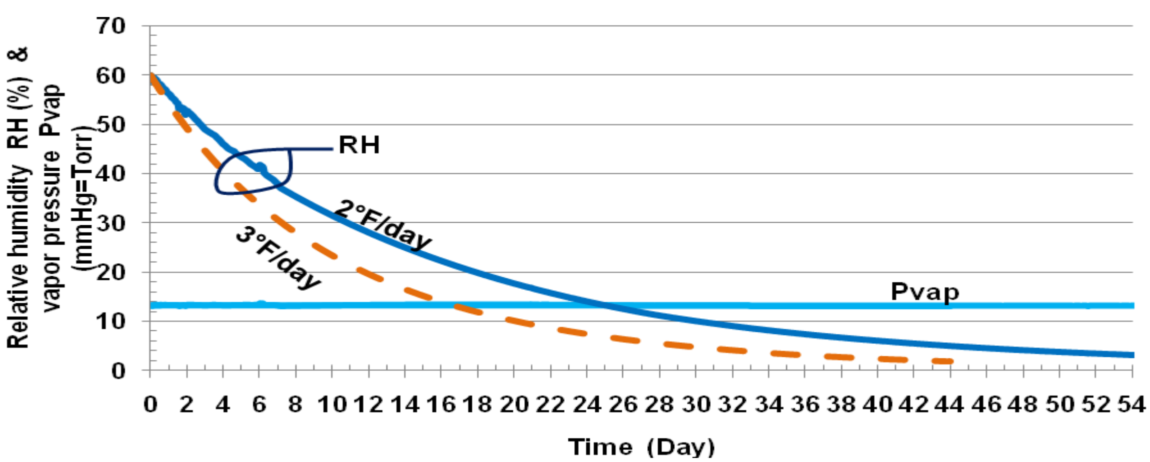
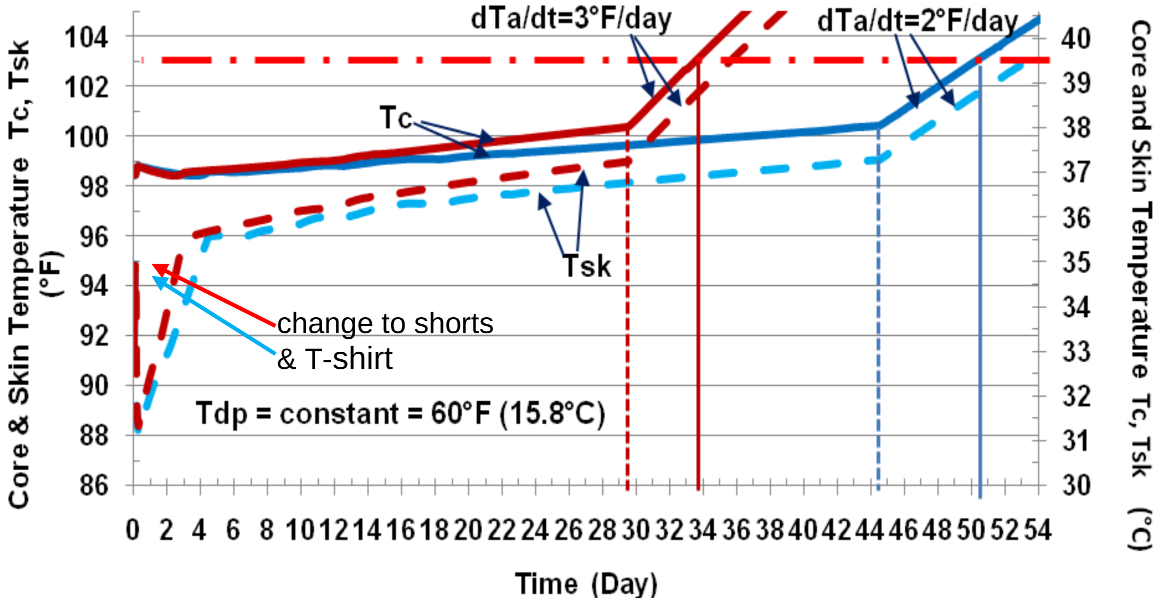


Figure 10c. SCENARIO_J simulation of core and skin temperature of medium built sailor resting in a disabled submarine with constant dew point of 60°F (15.8°C) but with T_a rising at 3°F/day and 2°F/day (1.66°C/day and 1.11°C/day), starting from 75°F (24°C)/60% RH.



In comparison to uncontrolled cabin humidity, the safe stay times with humidity held constant at initial levels (Figure 10c) are much longer than those with rising humidity (Figure 8c and Table 2). The constant low water vapor pressure in the air enables sweat to evaporate and be an effective cooling mechanism longer and compensates the higher cabin temperatures.

Figure 10d. Simulation of heart rate (dotted line) and physiological strain index (PSI, solid lines) of a medium-built sailor resting in a disabled submarine with constant dew point of 60°F (15.8°C) but T_a rising at 3°F/day and 2°F/day (1.66°C/day and 1.11°C/day), starting from 75°F(24°C)/60%RH.

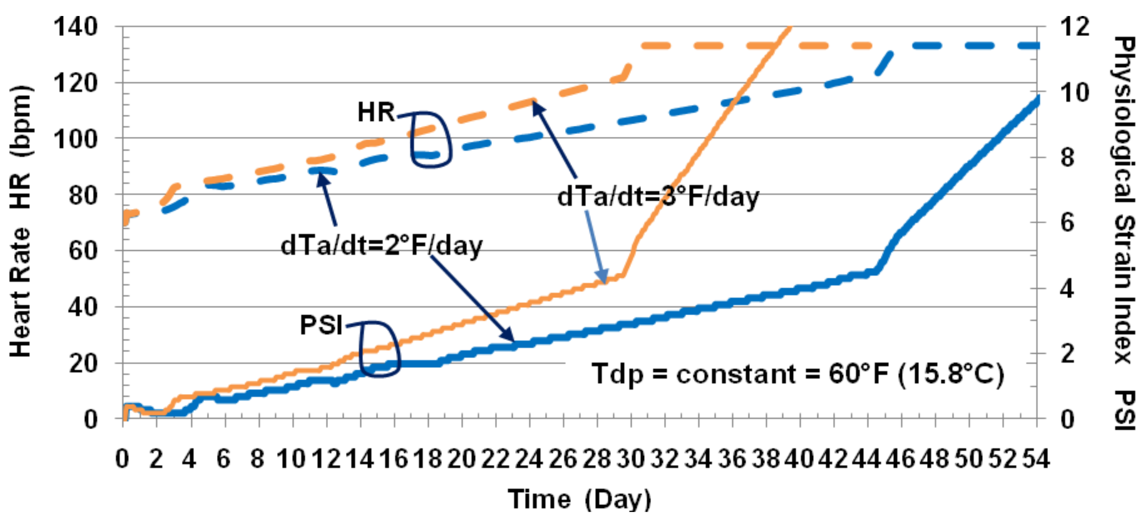
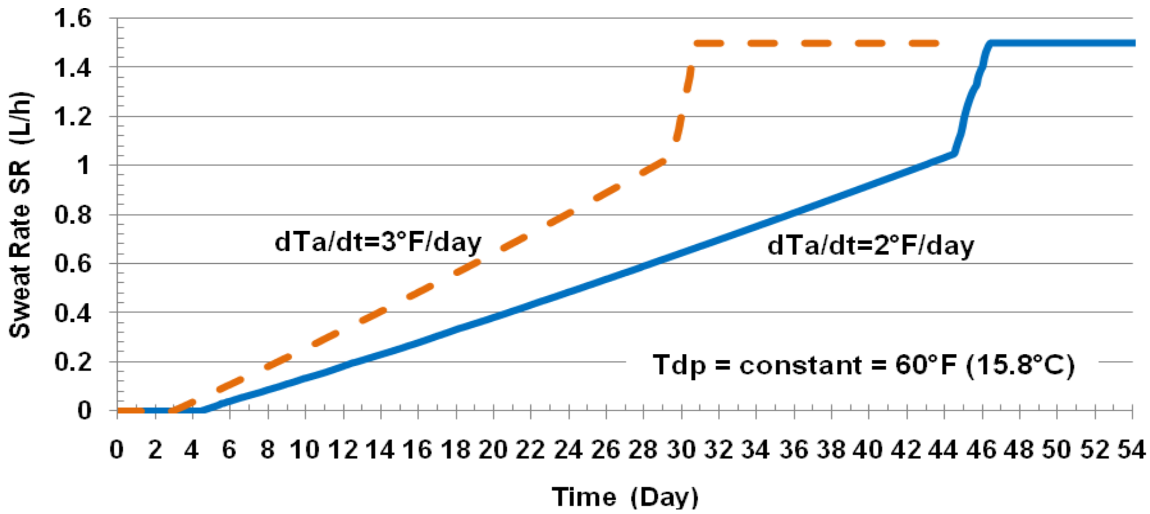


Figure 10e. Simulation of sweat rate responses of medium built 50th percentile sailor in disabled submarine with constant dew point of 60°F (15.8°C) but T_a rising at 3°F/day and 2°F/day, starting from 75°F (24°C)/60% RH and wearing long sleeved shirt and trousers but changed into shorts and T shirt quickly after disablement.



2) Constant Relative Humidity

The effects on un-acclimated medium built sailors to constant RH but rising T_a are illustrated in the following graphs (Figures 11a-f). As in previous simulations the occupants are resting and initially wearing a long sleeved shirt and trousers but change into shorts and T-shirt soon after disablement. All Figure 11 simulations are for T_a rising at the rate of 1°F/day (0.56°C/day).

Figure 11a. Simulation of environment in disabled submarine with air temperature (T_a) rising at 1°F/day (0.55°C/day) from an initial 75°F (24°C) and 60% relative humidity (RH) condition with RH held constant after a rise from the starting level.

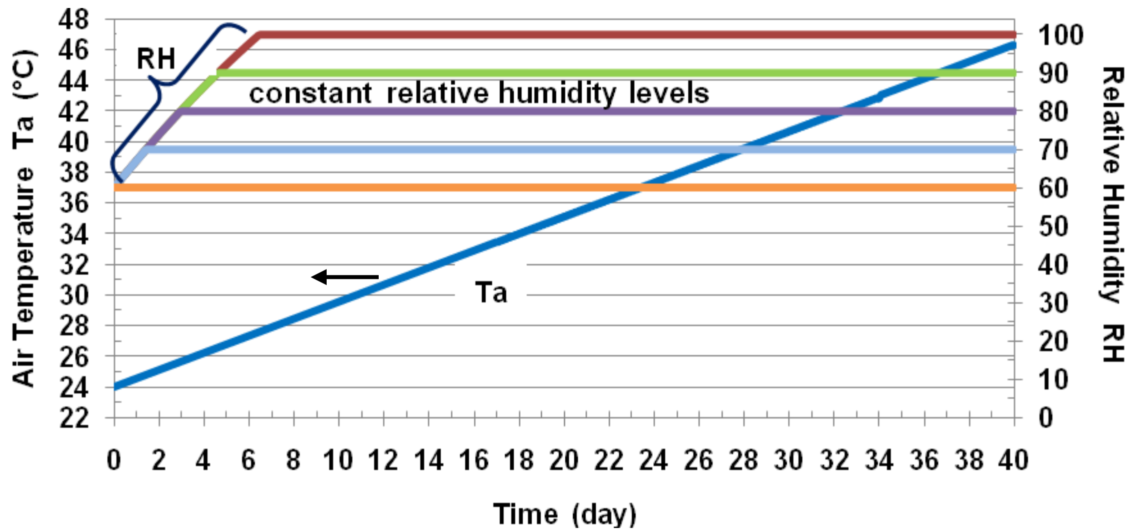
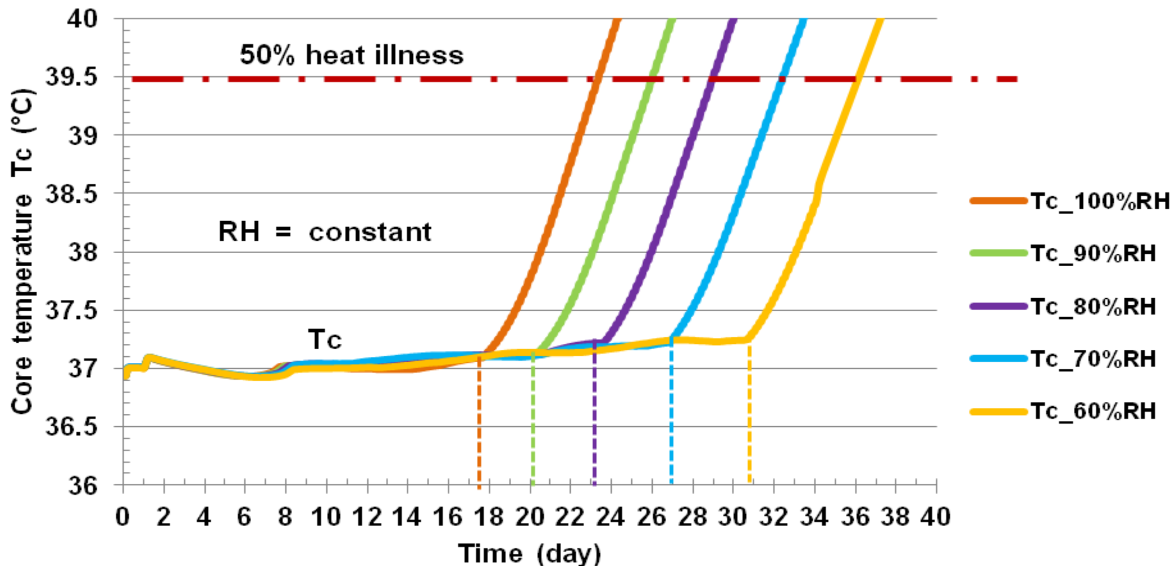


Figure 11b. SCENARIO_J simulation of core temperature of a resting medium built sailor in a disabled submarine with relative humidity (RH) held constant after rise from starting level and with air temperature (T_a) increasing at 1°F/day (0.55°C/day) from initial 75°F (24°C) and 60% RH condition. After day1, the sailors are wearing shorts and T-shirt.



Sailors are wearing long sleeved shirt and trousers at disablement but change into shorts and T-shirt as indicated by rapid drop in T_{sk} (Figure 11c).

Figure 11c. SCENARIO_J simulation of skin temperature of a resting medium built sailor in a disabled submarine with relative humidity (RH) held constant at indicated levels and with T_a rising at 1°F/day (0.55°C/day) from initial 75°F (24°C) and 60% RH condition.

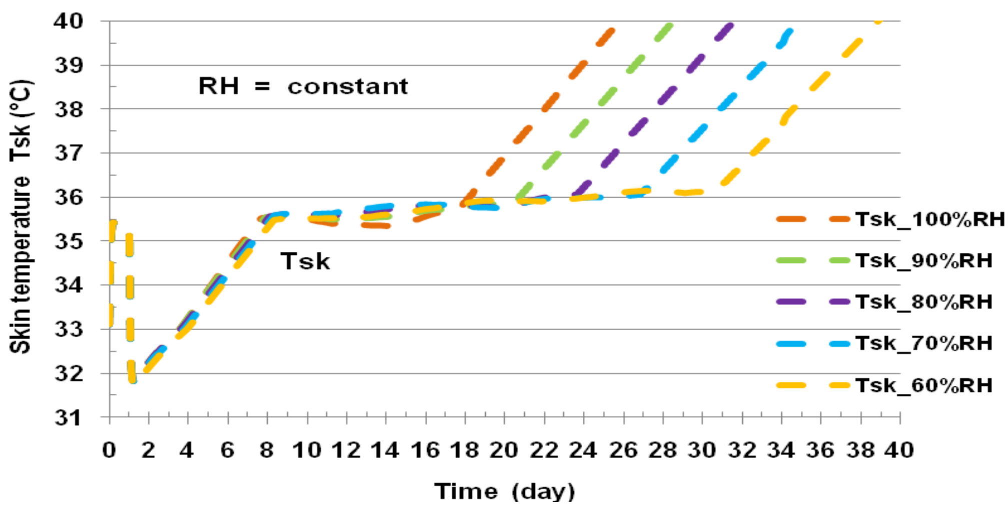


Figure 11d. Heart rate response of resting 50th percentile sailor in a disabled submarine with RH held constant and with T_a rising at 1°F/day (0.55°C/day) from initial 75°F (24°C) and 60% RH condition.

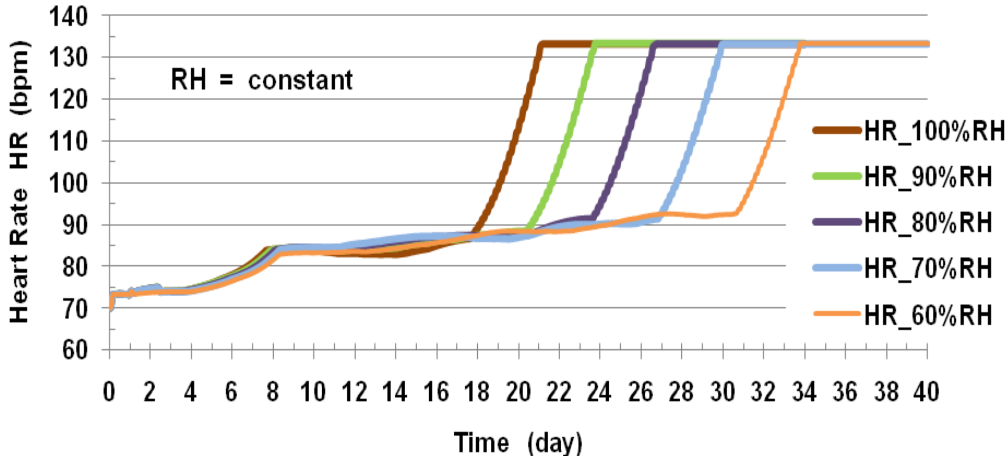


Figure 11e. Simulation of PSI responses of 50th percentile sailor resting in a disabled submarine with RH held constant after rising from starting level and with T_a rising at 1°F/day (0.55°C/day) from initial 75°F (24°C) and 60% RH condition.

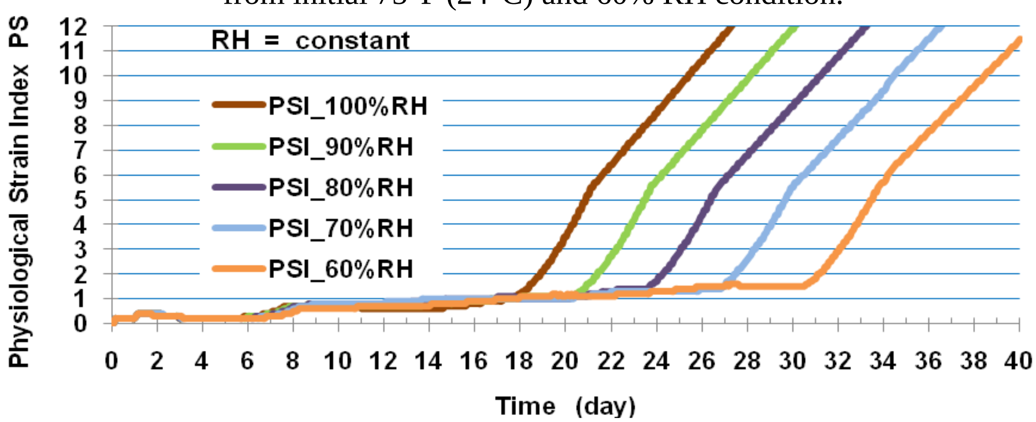
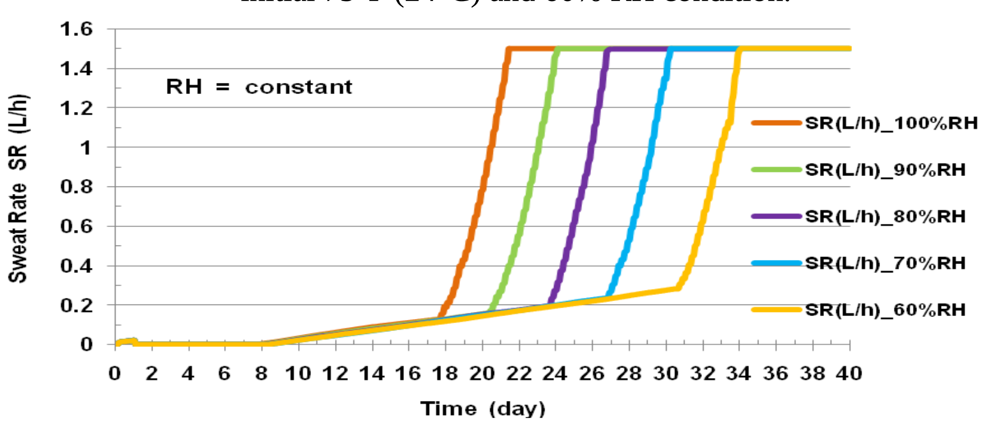


Figure 11f. Simulation of sweat rates of resting 50th percentile sailor in disabled submarine with RH held constant after rising from starting level and with T_a rising at 1°F/day (0.55°C/day) from initial 75°F (24°C) and 60% RH condition.



The evironmental and time limit values of Figure 11b are summarized in Table 3. The table gives the results for a temperature rise rate of 1°F/day. For other slow rates of temperature change (X °F/day) the elapsed time (Δtx) of an event can be estimated by:

$$\Delta tx = (\Delta tx \text{ for } 1°F/day)/(X°F/day).$$

Table 3. Summary of values from Figure 11a,b and e for constant relative humidity (RH) and time where core temperature (T_c) regulation begins to fail, T_c = 38.5°C, T_c = 39.5°C, and PSI = 10 with submarine's interior air temperature rising at 1°F/day starting from 75°F (24°C) and 60% RH and sailors resting in shorts and T-shirt.

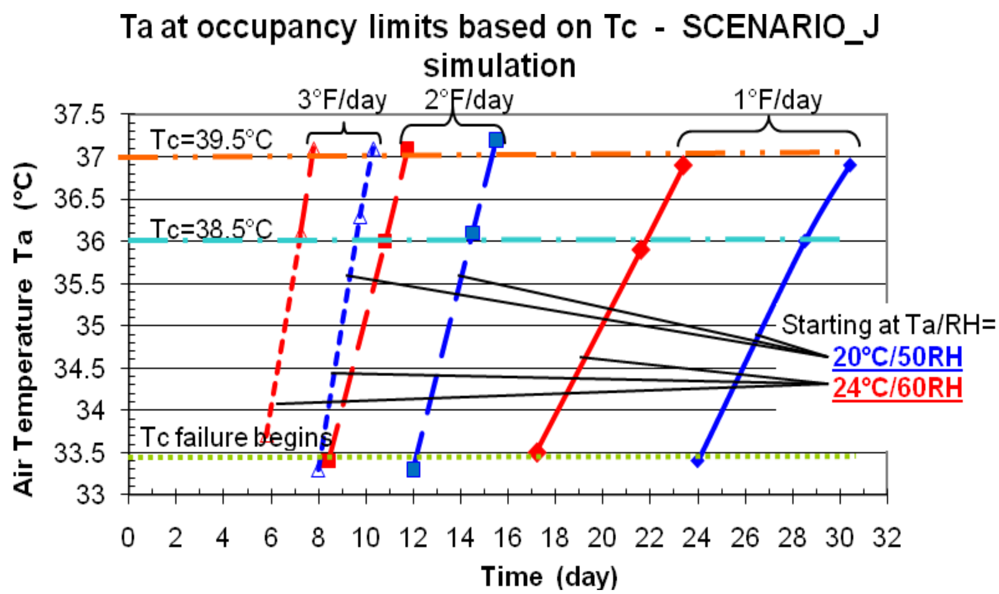
	Tc regulation begins to fail			Tc reaches 101°F (38.5°C)		Tc reaches 103°F (39.5°C)		Tc reaches 105°F (40.5°C)		PSI reaches 10	
RH (%)	time (day)	Ta °F(°C)	Tc °C	time (day)	Ta °F(°C)	time (day)	Ta °F(°C)	time (day)	Ta °F(°C)	time (day)	Ta °F(°C)
100	17.5	92(33.4)	37.08	21.5	96.8(37)	23.3	98.6(37)	25.25	100.4(38)	25.4	100(38.1)
90	20.2	95.4(35.2)	37.12	24.1	99(37.2)	26	101(38.4)	27.8	103(39.5)	28.1	103(39.5)
80	23.5	98.6(37)	37.22	27	102.2(39)	29	104.2(40.1)	31	106.2(41.2)	31.1	106.2(41.2)
70	26.8	102(38.9)	37.22	30.4	105.4(40.8)	32.4	109.9(43.2)	34.3	109.8(43.2)	34.4	109.8(43.2)
60	30.6	105.6(40.9)	37.25	34.1	109.4(43)	36.2	111.6(44)	38.25	113.5(43.3)	38.4	113.5(45.4)

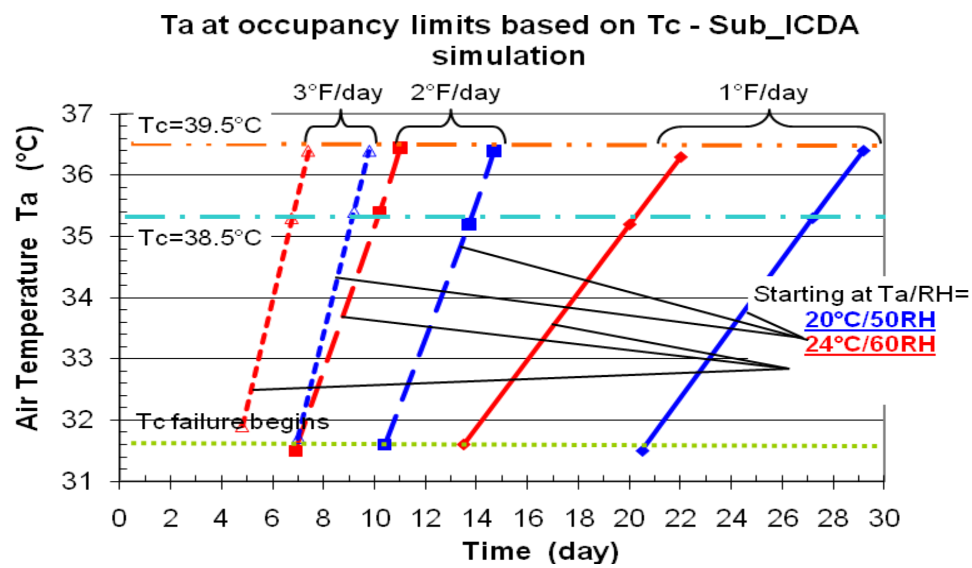
COMPARISON OF AIR TEMPERATURE LIMITS AND THE TOLERANCE TIME AFTER DISABLEMENT AS PREDICTED BY SCENARIO_J AND SUB_ICDA MODELS

The predicted T_a and times to reach the beginning of T_c regulation failure and also for T_c to reach 101°F (38.5°C) and 103°F (39.5°C) are displayed in Figure 12 for the SCENARIO_J and Sub-ICDA models. The predictions are for 3 rates of temperature rise and 2 starting points. The air temperatures at which T_c fails, reaches 101°F (38.5°C) and 103°F (39.5°C) are independent of the T_a rise rates and starting conditions for both models. This is because the three rates (1, 2 and 3°F/day) of temperature rise are very slow, enabling the sailor's physiology and body temperatures to adjust and be in a quasi-steady condition with the environment.

The T_a levels for the T_c limits indicated in Figure 12 are for disabled submariners with uncontrolled humidity that rises and reaches 100% RH before the sailor's T_c begins to rise rapidly from progressive insufficient heat loss and T_c regulation failure. The T_a at the T_c limits by the two models are very similar. The Sub_ICDA model consistently predicting the limits to occur about 0.6°C (1°F) lowerT_a , except at beginning of T_c regulation failure that is about 1.6°C (3°F) lower than the T_a SCENARIO_J model predicts.

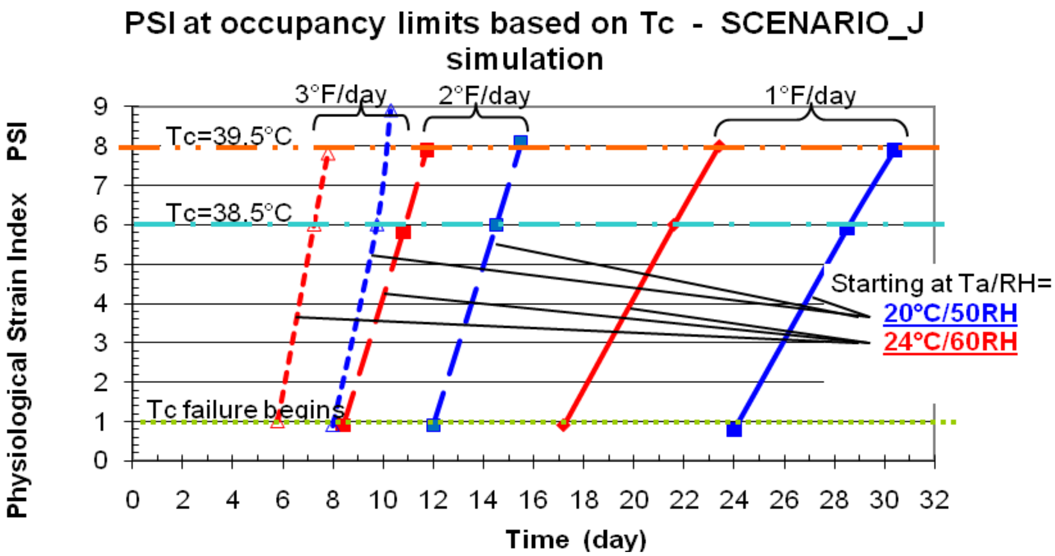
Figure 12. Comparison of air temperatures (T_a) where core temperature (T_c) regulation begins to fail, T_c reaches 38.5°C and 39.5°C (101.3°F and 103.1°F) after dissablement as predicted by SCENARIO_J (upper graph) and Sub_ICDA (lower graph) models.

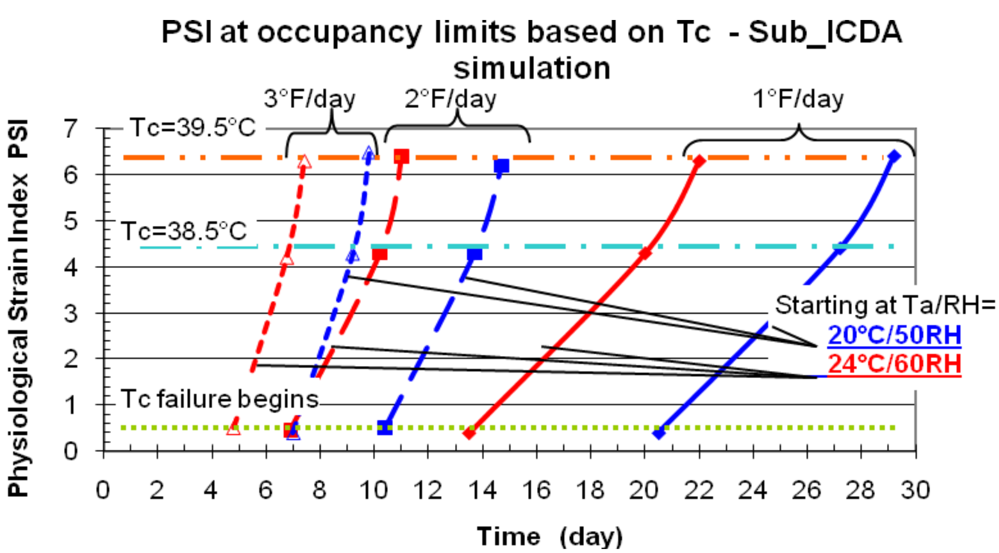




A comparison of PSI levels predicted by the models at the T_c limits and times are displayed in Figure 13. The agreement is again consistent with Sub _ICDA predicting about 1.7 PSI units less strain at the 38.5°C and 39.5°C T_c limits and 0.5 units less at the beginning of T_c failure.

Figure 13. Comparison of physiological strain (PSI) predictions by SCENARIO_J (upper graph) and Sub_ICDA (lower graph) at equal environmental conditions.





The T_a , time and PSI values of Figures 12 and 13 for the two modeling systems are summarized in Table 4. As noted above, the T_a's and their occurrence times predicted by the models are very similar, particularly for when T_c reaches 101°F (38.5°C) and 103°F (39.5°C). The T_a are generally a little lower and occur sooner for the Sub_ICDA response predictions.

The coincident PSI levels are also lower for Sub_ICDA at the T_c limits. The SCENARIO_J model has the more complete and developed thermal physiological control mechanisms, and may be the more accurate predictor for this situation. But the differences are small and the response patterns are similar making both, or their average, good guidelines for rescue planning.

Table 4. Summary of time elapsed since disablement, cabin T_a, and sailor's PSI values where: T_c regulation begins to fail, T_c=101.3°F (38.5°C) and T_c=103°F (39.5°C) as predicted by SCENARIO_J and Sub_ICDA models for resting sailors in shorts and T-shirts. The disabled submarine's humidity 100% RH before T_c regulation begins to fail and remains at 100% RH thereafter .

			Tc regulation begins to fail				Tc =101.3°F(38.5°C)				Tc=103°F(39.5°C)			
model	dTa/dt	starting at	time	Ta	Ta	PSI	time	Ta	Ta	PSI	time	Ta	Ta	PSI
	°F/day	°F(°C) /%RH	day	°F	°C		day	°F	°C		day	°F	°C	
ScenarioJ	1	75(24)/60	17.5	92.1	33.4	0.9	21.5	96.6	35.9	6	23.4	98.4	36.9	8
	2		8.4	92.1	33.4	0.9	10.8	96.8	36	5.8	11.8	98.8	37.1	7.9
	3		5.8	92.67	33.7	1	7.25	97	36.1	6	7.8	98.8	37.1	7.8
	1	68(20) /50	24	92.1	33.4	0.8	28.5	96.8	36	5.9	30.4	98.4	36.9	7.9
	2		12	91.9	33.3	0.9	14.5	97	36.1	6	15.5	99	37.2	8.1
	3		8	91.9	33.3	0.9	9.75	97.3	36.3	6	10.3	98.8	37.1	8.9
	ave			92.1	33.4	0.9		96.9	36.1	5.95		98.7	37.1	8.1
Sub-Icda	1	75(24)/60	13.5	88.9	31.6	0.4	20	95.3	35.2	4.3	22	97.3	36.3	6.3
	2		6.9	88.7	31.5	0.45	10.2	95.7	35.4	4.3	11	97.6	36.45	6.4
	3		4.8	89.4	31.9	0.5	6.75	95.5	35.3	4.2	7.4	97.5	36.4	6.3
	1	68(20) /50	20.5	88.7	31.5	0.4	27.2	95.5	35.3	4.4	29.2	97.5	36.4	6.4
	2		10.4	88.9	31.6	0.5	13.7	95.4	35.2	4.3	14.7	97.5	36.4	6.2
	3		7	89.1	31.7	0.4	9.2	95.7	35.4	4.3	9.8	97.5	36.4	6.5
	ave			88.9	31.6	0.44		95.5	35.3	4.3		97.5	36.4	6.35

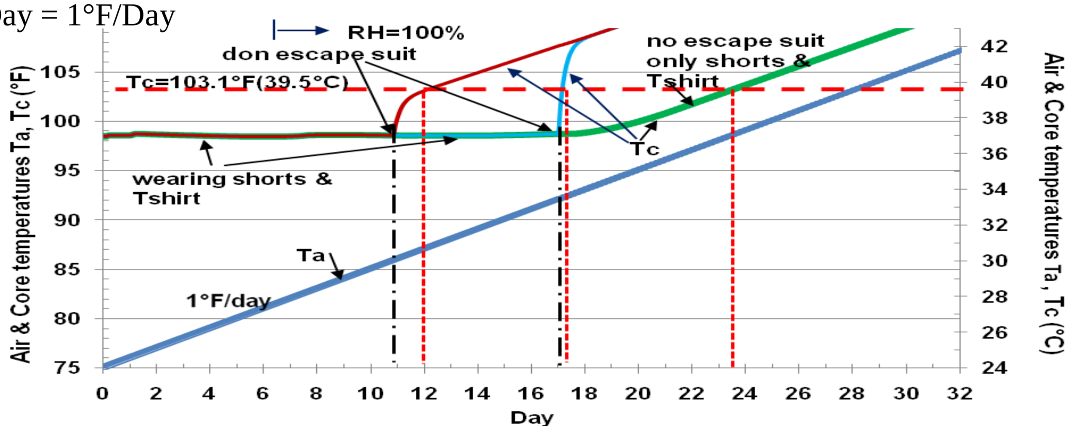
Escape

Previous model simulations are based on conditions for the resting sailor wearing shorts and T-shirt or similar clothing to survive longer periods of time in a disabled submarine. However, escape from the disabled submarine may necessitate wearing an escape suit. Unfortunately for these warm conditions, the impermeable escape suit eliminates possible evaporative cooling from sweating; causing the sailor's T_c to rise more rapidly and shortens the time available for safe crew rescue. Physiological responses to the disabled thermal conditions were estimated by the SCENARIO_J model for the 50th percentile sailor donning the escape suit when the T_a reaches 86°F (30°C) and also when thermal regulation begins to fail at an air temperature of 92°F (33°C) with 100% RH.

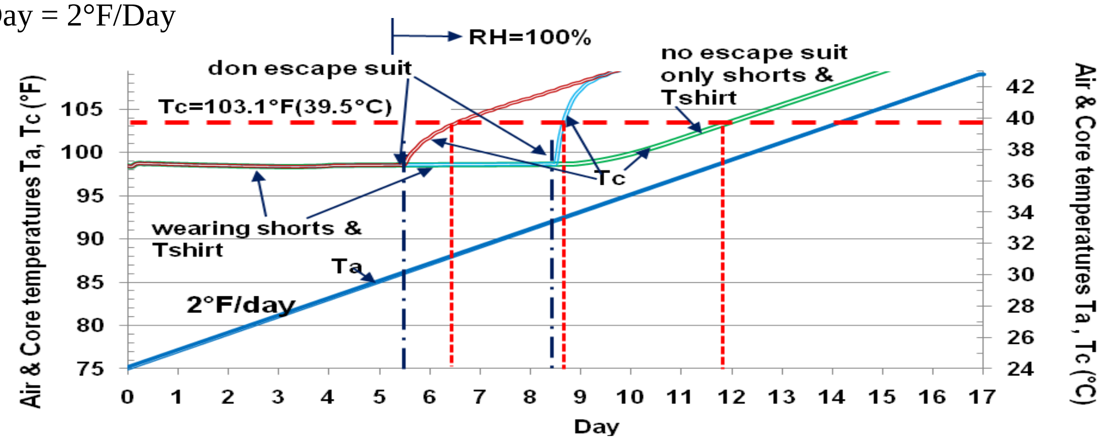
The T_c responses are displayed in Figure 14 for 1, 2 and 3 °F/day rates of T_a rise. Donning the escape suit at 92°F conditions causes T_c of the resting sailor to reach the unsafe 103°F (39.5°C) level in about 2 hours. If the suit is put on earlier when the interior temperature is 86°F (30°C), the time available before reaching 103°F (39.5°C) increases to about 1 day irrespective of the rate of temperature rise. Figure 14 strongly indicates that the wearing of the escape suit should be delayed until the escape begins, and avoided if possible in such thermally challenging situations.

Figure 14. Core temperature responses to donning an escape suit at: 1) T_a = 86°F (30°C), 2) T_c regulation begins to fail, and 3) not donning the escape suit. Cabin temperature is rising at 1°F/day (upper graph), 2°F/day (middle), and 3°F/day (lower graph), starting from 75°F (24°C) and 60% RH. Humidity is uncontrolled and reaches 100% RH as indicated at top of each graph. Time axes of graphs have different day lengths.

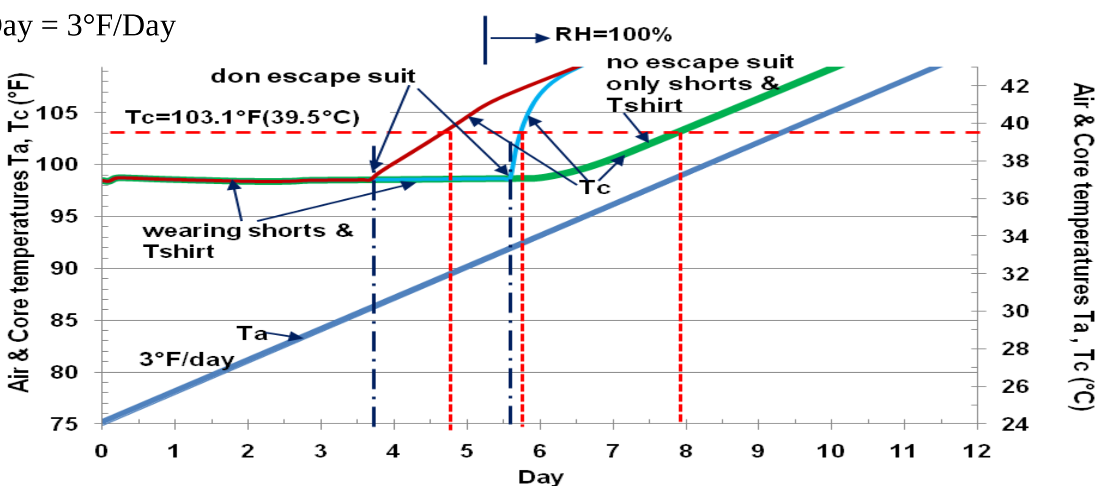
ΔT_a/Day = 1°F/Day



ΔT_a/Day = 2°F/Day



ΔT_a/Day = 3°F/Day

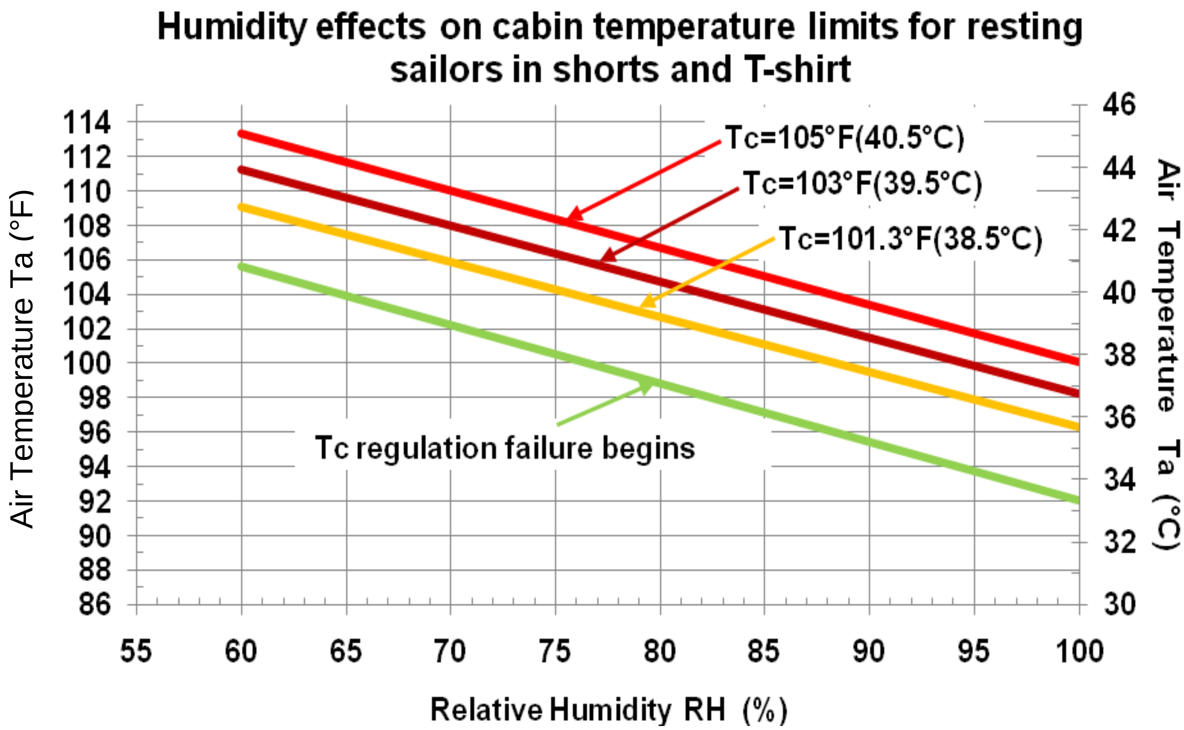


DISCUSSION

The sailor response predictions were made with reliable USARIEM thermo-physiological models developed and validated for warm environments. The simulations estimate human responses to a loss of power in an intact vessel resulting in a slow steady increase of air temperature and humidity in the submarine's occupied compartments. In some disablements equipment damage, water leaks and personal injuries may impose additional stress and strains on the sailors altering the assumed modeled conditions and resting activities while waiting for the rescue. Increasing the average metabolic activity of the crew will in general shorten the time available for safe successful rescue. Further, the study assumes the submarine's occupied compartment temperatures can increase without limit. However, depending on the situation, air temperature upper limits will likely develop limiting potential thermal stress. Because of these possible unknowns in modeling the responses of the crew and also the condition of the submarine after disablement, the results of this study should be considered as rational guidelines and be compared to observations and measurements when possible as they become available or are discovered from applicable sea and laboratory experiences.

The sailor's responses to the slow rise of temperature in the disabled submarine have been simulated for a wide range of conditions. The results have similar repeatable patterns. The gradual temperature and humidity increase permits the sailors thermoregulatory system to be in a quasi equilibrium state with the environment. This is fortunate and enables the environmental parameters important for heat exchange to be reasonable and reliable indicators of the sailor's thermo-physiological state. Figure 15, developed from simulation results, based on Tables 2, 3 and 4 summarizes the relationship between the environmental temperature and humidity with quasi-steady states of body T_c for the resting sailor wearing shorts and T-shirt or similar clothing. The body temperatures are independent of the rate of temperature for rates <6°F/day. Thus the easily measured air temperature and humidity of the occupied spaces is a good indicator of the thermal health state of the occupants. And they can both be readily and reliably measured. The time for the average sailor to reach the beginning of T_c regulation failure, and or T_c = 101°F (38.5°C), T_c = 103°F (39.5°C) and T_c = 105°F (40.5°C) can be estimated from initial temperature, the rate of T_a rise, and the T_a for the event from Figure 15 and equation [4], as explained in example 1.

Figure 15. The air temperature and humidity levels for indicated body core temperatures of resting crew in a disabled submarine with slowly increasing temperature.



Elapsed time since disablement for T_c to reach a level indicated in Figure 5

$$\text{Elapsed time} = (T_a@T_c - T_a@\text{disablement})/(\text{average } T_a \text{ rise})$$

Example 1., Time to when T_c regulation begins to fail with RH=75% and an average T_a rise of 2.2°F/day, starting from disablement cabin air temperature of 71°F. From figure 15 at T_c fails & 75%RH, T_a=101.5°F. Then, substituting into equation 4, the elapsed time = (101.5-71)/2.2=13.86 days and T_c regulation failure begins at 37.22°C (99°F) (Figure 15).

Example 2. When T_a is 98°F and RH is 95%, then quasi-steady state of T_c is approximately 101.3 °F (Figure 15).

CONCLUSIONS

Thermo-physiological responses of crew members to the gradual but unrelenting accumulation of heat and humidity possibilities in a disabled submarine were simulated with USARIEM computer modeling tools. The modeling indicates that the resting medium body size (50^{th} percentile) sedentary and lightly clad sailor, waiting for rescue, would begin to experience a rapid rise in body temperature and thermo-regulatory failure at an air temperature (T_a) about 92°F (33°C) together with humidity near saturation (95-100% RH). The humidity rise was assumed to be driven by water vapor evaporating from the crew. From that point on, it will take 6 more days with a 1°F (0.6°C)/day rate of $T_a$rise for the individual's T_c to reach the unsafe 103°F (39.5°C) level, and 3 and 2 days with 2°F (1.1°C) and 3°F (1.7°C)/day rise conditions, respectively. Heat acclimation status appears to have minimal effect on final body temperatures and rescue time limits. Short- lean sailors will be slower in reaching unhealthy body temperatures and sailors with large body size will arrive at these levels sooner. The time available for the rescue can be lengthened by cooler and dryer initial pre-disablement conditions. Also reducing or slowing the rise of humidity has a strong beneficial effect on thermoregulation with rising warm temperatures.

At 92°F (33°C) with high humidity the individual is relying on sweat evaporation to carry away body heat. Donning an impermeable escape suit eliminates the evaporative cooling from sweating, causing T_c to rise rapidly. At 92°F (33°C) conditions in the escape suit, T_c reaches 103°F (39.5°C) in about 2 hours. If the suit is put on earlier when the interior temperature is 86°F (30°C), the time available before reaching 103°F (39.5°C) increases to about 1 day irrespective of the rate of temperature rise. This strongly indicates that the wearing of the escape suit should be delayed until the escape begins, and avoided if possible in such situations.

RECOMMENDATIONS

The project developed a useful graph (Figure 15) indicating cabin temperature and RH conditions that correspond to: 1) beginning of thermoregulatory failure and rapid rise of T_c, 2) T_c = 101.4°F (38.5°C), 3) T_c = 103°F (39.5°C), and 4) T_c = 105°F (40.5°C). As T_a and RH can be readily measured by the crew, the graph may help estimate the thermal health status of the sailors and guide rescue activities after disablement. Further, the graph and accompanying Tables 2, 3 and 4 can be used to estimate the expected time to reach these various health states.

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APPENDIX A

Listing of Sub_ICDA source code

```
/*
Origin: BBMD @ USARIEM
Authors: Berglund and Yokota
Date: 3/31/08
File:  Sub_ICDA_HRk_360_3_31_08.c

This simulates the thermal physiological responses(Tc,Tsk,sweat, skin
diffusion and repiratory waterLoss,skin wettedess,HR, PSI) from inputs of
metabolism, environmental parameters(Ta,RH,V, Air Volume)and constant
personal properties(ht,wt %Bfat) and clothing.

The constant personal properties,and initial physiological values are entered
through the keyboard. The metabolism and other parameters are entered at
different simulation times are read from a textfile. The interval (in
seconds) between measurements is adjustable. Enter 0 for the default interval
of 300sec(5min).

The measured values (min,met) are read from a txt file. See SubIn2.txt for an
example of input's form and spacing(consecutive 10 digit spaces for each min
of measurements).

The output is displayed on screen and written(appended)to output.txt file.
The output of predicted responses occur after each integration step.

The program's integration step is adjustable. Enter 0 for the default
integration step interval of 60sec.The default value is a good choice. for
slow changing situations  interval step can be longer and a shorter interval
for responses to rapidly changing stituations.

Metabolism is expressed by dimenionless relative metabolism term(met) where
met=actual_metabolism/resting_metabolism.

intrinsic clo is thermal resistance from skin to outer layer of clothing in
clo units.
MRT= mean radiant temperature
V=air speed m/s.
*/

#include <assert.h>
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <ctype.h>

#define Pbar 760.       //atmospheric pressure mmHg
#define TTSK 33.7     //°C
#define TTCR 36.8     //°C
#define TTBM 36.49    // TTBM=.9*TTCR+.1*TTSK =36.49
#define CSW 170.      // g/(h m^2 °C)
#define CDIL 50.      // CDIL 200 super athlete, 50 average person
#define CSTR .5       //  1/°C
#define SKBFN 6.3     // liters/(h m^2)
#define     Skbfmax 90.  // conservative could be higher for fit person
```

```
#define Skbfmin 2.    //Liters/(h m^2)
#define CMIN 5.28     // w/(m^2 °C)
#define Clave 3200.    //  mlBlood/(m^2*min)
#define FO2ExtCr .10  //fraction of O2 extracted from blood flowing through
core
#define FO2ExtMu .80  //fraction of O2 extracted from blood flowing through
muscle
#define BLO2cap .21  //mlO2/mlBlood
#define O2equiv 2.93 //mlO2/(w*min)
#define CB 1.163      // wh/(L °C)
#define WpMet 58.2    //  w/(m2*met)
#define LR 2.2        //Lewis relation  °C/mmhg

void OutputHeader();

double SatVapPres(double T);          // in Torr = mmhg
double Clot(int code, double V);     //total clo from skin to environment
double VRes(int code, double V); //total vapor resistance from skin to
environment
double Convection(double met, double V);//convective heat transfer coef
double Respiration(double Rm, double Ta, double Pa,double* Wres);
//respiratory heat loss
double SkinBloodFlow(double Tc, double Tsk);
double Shiver(double Tc, double Tsk,double* Bfat);
double DuBoisSkinArea(double Wt, double Ht);   //surface area of body
double O2pkg(double Bf, double HR);
double BflowCore(double mtot,double HRRk);
double BflowMuscle(double mtot,double Bfc);
double StrokeVolume(double Adu, double HRrest,double Tsk);
double BreathRate(double met,double Wt,double Adu);
double MetT(double HR,double HRrest,double T);
double HeartRate(double met,double T, double HRrest); //from ICDA
double Alpha(double Skbf);                        // fraction of body that is skin
double Sweat(double Tc, double Tsk,double alpha);
double Core(double Tc,double Tsk,double met,double Res,double* hfcsk, double
skbf,double* Rm, double* Bfat);
double Skin(double wet,double Dry,double Emax,double* hfcsk);
double MoranPSI(double Tc,double Tco,double HR,double HRrest); //heat stress
index

int main (void)
{
    int step, code;
    double Age,Ta,Tao,Ta_rise,MRT,RH,RHo,Pa,Psa,Psk,Tcl,To,V,Vps,ma,HRkmax;
    double HRRk,hc,he,hr,met,Metnew,Ht,Wt,Adu,Wres,drip,DT,DTs,DTM,DTMP,Res;
    double DTMH,ExTime,MeasTime;ReadTime,PrintTime,rhoa,clos,cloDisSub,Emax;
    double CEvapWLL,VO2max;wet,Tdpa,Tsk,Tsko,Tc,Tco,Rm,clo,FACL,Dry,PSIc,BMI;
    double Esk,Edif, Skbf,HRrest,HR,alpha,Regsw,Ersw,Wi,Wo,Wos,Wdif,Wsk_evap;
    double Wevap,heatFlowCoreToSkin,HSCR,HSSK,TCCR,TCSK,Rcl,Rbound,Rclt,Rpcl;
    double Rpbound,Rpclt,Bf,Bfc,Bfm,Bfat,SV,CEvapWL,CdripL time,TIM,MTIM;
    double Duration,CumulativeWaterLossPsqm,CWLL; CumulativeWaterLoss;
    doubleRateOfTotalWaterLossPsqm,RateOfTotalWaterLoss;
    char inName[64], outName[64];
    FILE *pifile=NULL;           //file pointer to inputfile
    FILE *pofile=NULL;           //file pointer to outputfile
    char *inputfilename=inName;
    char *outputfilename=outName;
```

```
    // get file names from user
    printf("Enter name of inputfile: xxxx.txt ");
    scanf ("%63s", inName);
    printf("Enter name of outputfile(<30char): xxxxx.txt ");
    scanf ("%63s", outName);

    TIM=0; MTIM=0; step=0; time =0; HR=0; HRrest=0; DTs=0; ExTime=0;
    ReadTime=0; MeasTime=0; PrintTime=0; Wo=0; Wos=0; Wi=0; drip=0;
    Wo=0; Wos=0; Wi=0; CumulativeWaterLossPsqm=0; CumulativeWaterLoss=0;
    CWLL=0; CEvapWL=0; PSIc=0; Regsw=0; CEvapWL=0; CdripL=0;

    printf("Enter time-step for discrete integration in seconds(0 for default
of 60 seconds):DTs  ");
    scanf("%lf",&DTs);
    if (DTs<=0)
       DTs=60;      // default time step in seconds

    DT=DTs/(60*60);  //time step  DT in hrs
    printf("Enter interval between measurements in minutes(interval>=DTs)(0
for default of (60min):  ");
    scanf("%lf",&DTM);
    if (DTM<=0)
      DTM=60; /*time(min) between measurements  default value of 60 min
              between measured input */

    DTMH=DTM/(60);  //time between measurements  DTMH in hrs
    printf("Enter starting intrinsic clo(sailor fatigues=.6) : clo  ");
    scanf("%lf",&clos);
    code=0;
    FACL=1+.2*clos;    //estimate of outside area of clothed person
    Rcl=.155*clos;
    Rpcl= .153181*clos;  /* Berglund 1985,for icl=Rcl/(LR*Rpcl)=.45;
                          Rpcl=.155*clo/(LR*icl)=.155*clo/(2.2*.45) */
    clo=clos;
    printf("Enter DisSub intrinsic clo(shorts,Tshirt,sandals=.2) : clo  ");
    scanf("%lf",&cloDisSub);

    printf("Enter subject's weight(kg),height(m) (or 0's if unknown): Wt Ht
");/* inserts default values of 82kg,1.77m */
    scanf("%lf%lf",&Wt,&Ht);
    if (Wt<=0)
       Wt=82;
    if (Ht<=0)
       Ht=1.77;

    printf("Enter subject's %BFat (or 0's if unknown): Bfat ");/* inserts
                                                  default values of 15% */
    scanf("%lf",&Bfat);
    if (Bfat<=0)
       Bfat=15;

    printf("Wt=%7.3f kg, Ht=%7.3f m, Bfat=%8.4f \n", Wt,Ht,Bfat);
    Adu=DuBoisSkinArea(Wt,Ht); //m^2

    printf("Enter subject's resting HR,age and VO2max(ml/min/kg)(or 0's if
unknown):HRrest Age VO2max ");/*inserts default values of 70,23,51.4 for
```

```
                                  zero's */
scanf("%lf%lf%lf",&HRrest,&Age,&VO2max);
if (HRrest<=0)
   HRrest=70;
if (Age<=0)
   Age=23;
if (VO2max<=0)    //ml/(min kg)
   VO2max=51.4;

printf("Enter initial physiology (or 0's if unknown): Tsk Tc HR met ");/*
                                 inserts default values if Tsk,Tcr are zero's */
scanf("%lf%lf%lf%lf",&Tsk,&Tc,&HR,&met);
if (Tsk <=0){
   Tsk=33;
   Tsko=Tsk;
}
else
   Tsko=Tsk;

if (Tc <=0){
   Tc=36.9;
   Tco=Tc;
}
else
   Tco=Tc;

if (HR<=0)
   HR=HRrest;
if (met<=0)
   met=1;
Rm= met*58.2;
HRkmax=220-Age;
HRRk=HR/HRkmax;
BMI=Wt/(Ht*Ht);
wet=.06;
printf("Enter initial environment (or 0's if unknown): Ta RH V ");/*
                           inserts default values if Ta,RH V are zero's */
scanf("%lf%lf%lf",&Ta,&RH,&V);
if (Ta <=0){
   Ta=24;
   Tao=Ta;
}
else
   Tao=Ta;

if (RH <=0){
   RH=60.;
   RHo=RH;
}
else
   RHo=RH;

if (V<=0)
   V=.05;

  MRT=Ta;
```

```
	printf("Enter air volume per sailor and initial rate of Ta rise (or 0's
if unknown): Vps Ta_rise ");/*inserts default values if Vps,Ta_rise are
					zero's */
	scanf("%lf%lf",&Vps,&Ta_rise);	//units  m^3,	C/day

	if (Vps <=0)
	   Vps=360;	//m^3

	if (Ta_rise<=0)
	   Ta_rise=1.11;   // 2F/day = 1.11C/day=1.11/24 C/h

	Pa=RH*SatVapPres(Ta)/100;	// ambient vapor press Torr
	Tdpa=4030.183/(18.6686-log(Pa))-235;
	Wi=.622*Pa/(Pbar-Pa);	  // initial humidity ratio  kgw/kga
	Wo=Wi;
	rhoa=(Pbar-Pa)*133/((Ta+273)*8315/28.97);  //density of dry air kga/m^3
	ma=rhoa*Vps;  // kg  of air
	printf("rhoa=%7.3f kg/m^3, ma=%7.3f kga, Wi=%8.4f \n", rhoa,ma,Wi);

	printf("Enter duration(hr)(0 for default=16days=384h):  "); /* may wish
				to delete duration for real applications */
	scanf("%lf",&Duration); // duration in hours, hr
	if (Duration<=0)
	   Duration=384; //16days

	printf("Enter interval in min between printouts(0 for default of
(360min=6hr):  ");
	scanf("%lf",&DTMP);  //DTMP in min
	if (DTMP<=0)
	   DTMP=360;  //6 hours

	pifile=fopen(inputfilename,"r");
	if (pifile==NULL)
	{
	   printf("\n Error opening %s for reading. Program terminated.",
inputfilename);
		exit(1);
	}
	printf("input file is open \n");
	pofile=fopen(outputfilename, "a");
	if(pofile==NULL)
	{
	   printf("can't open %s for appending.\n",outputfilename);
	   exit(2);
	}
	printf("output file is open \n");
	printf(" Air Volume= %4.1f m^3, V= %5.2f m/s, dTa/dday=  %5.2f C/day
\n",Vps,V,Ta_rise );
	printf("    wt= %5.1f kg, ht= %4.2f m, Bfat= %4.1f \n\n",Wt,Ht,Bfat);
	{
	   fprintf(pofile,"\n\n output file name: %30s \n", outName);
	   fprintf(pofile," Air Volume(m^3)= %f, V(m/s)= %f, dTa/dday=  %f
\n",Vps,V,Ta_rise  );
	   fprintf(pofile," wt(kg)= %f, ht(m)= %f,  Bfat= %f \n\n",Wt,Ht,Bfat);
	   fprintf(pofile," hr     Ta    clo    RH  Tdp    Wo     Tc     Tsk  met
sw   wet  HR  CWLos CdripL PSI \n"); //header for ouput file
```

```
        fprintf(pofile,"         C               C            C     C
g/min       bpm    L      L \n");
      }

      OutputHeader();  //used for screen display only
             //TIM  Ta    clo    RH    Tdp    Wo     Tc    Tsk    met    sw   wet
HR  CWLOS PSI
      printf("\n%6.1f %5.1f %4.2f%4.0f %5.1f %5.3f %5.2f %5.2f %4.1f %5.2f
%3.2f %3.0f %8.2f%4.1f",TIM,Ta,clo,RH,Tdpa,Wo,Tc,Tsk,met,Regsw/60*Adu,wet,HR,
CWLL,PSIc);
      fprintf(pofile,"\n%6.1f %5.1f %4.2f%4.0f %5.1f %5.3f %5.2f %5.2f %4.1f
%5.2f %3.2f %3.0f %8.2f %8.2f %4.1f",TIM,Ta,clo,RH,Tdpa,Wo,Tc,Tsk,met,
Regsw/60*Adu,wet,HR,CWLL,CdripL,PSIc);
      TIM +=DT;          // 0+1 time step  hr
      ReadTime+=DTM/60;        //time for next read in hr (default= 1hr)
      PrintTime+=DTMP/60;     //next time to print in hours
      Tcl=Tsk;    //a first guess

      //MeasTime+=DTM*60; // time in hr for next measuredInput
      time+=Duration;   //time in hr

      while (TIM<=time)// thermo-physiology loop start measure and print loop
      {
          MTIM=TIM;  //TIM in hr  MTIM in hr

          if (MTIM>=ReadTime){  /* if current time(MTIM)is > or = ReadTime
                 it reads file.  if not it assumea conditions are unchanged*/
             fscanf(pifile,"%10lf%10lf",&ExTime,&Metnew);
             ReadTime=ExTime+DTM/60;//nextread time & ExTime in hr
          }
          else {
             Metnew=0;
          }

          if (Metnew>0)
             met=Metnew;

          if (Tsk>34 ){
             clo=cloDisSub;
          }
          else {
             clo=clos;
          }

          FACL=1+.2*clo;     //estimate of outside area of clothed person
          Rcl=.155*clo;
          Rpcl= .153181*clo;

          //HR=HeartRate(met,Ta,HRrest);
          //met=MetT(HR,HRrest,Ta); //from Berglund 30th ACEMB,1977
          Bf= BreathRate(met,Wt,Adu);        //breathing rate
          Bfc=BflowCore(Rm,HRRk);          //  ml/(min*m^2)
          Bfm=BflowMuscle(Rm,Bfc);         //  ml/(min m^2)
          SV=StrokeVolume(Adu,HRrest,Tsk);  // ml
          Skbf=SkinBloodFlow(Tc,Tsk);        // Liters/(h m^2)
          HR=(Skbf*1000/60+Bfc+Bfm)*Adu/SV;  //bpm
          HRRk=HR/HRkmax;     //fraction of maximum heart rate
```

```
/* dry and evaporative heat transfer*/

 Psk=SatVapPres(Tsk);          //vapor press of water on skin Torr

 hc = Convection(met,V);          // convection
 he=2.2*hc;                       // evaporation   watts/(m^2 Torr)
 hr=4*.725*(5.67E-08)*pow(((Tcl+MRT)/2+273),3); // corrected hr
 To=(hc*Ta + hr*MRT)/(hc+hr);                //operative tempeature C

 if (code==0) {               //used intrinsic clo
   //Fpcl=1/(1+.153181*he*FACL*clo); //Berglund 1985, for IL=.45
    Rpbound=1/(he*FACL);
    Rpclt=Rpcl+Rpbound;
    Rbound=1/((hc+hr)*FACL);
    Rclt=Rbound+Rcl;
  }
  else {                       // used total clo
    Rclt=.155*Clot(code,V);
    Rpclt=VRes(code,V);
  }

  Emax=(Psk-Pa)/Rpclt;     //watts/m^2
  Dry=(Tsk-To)/(Rclt);     //watts/m^2
  Tcl = To +Dry/(FACL*(hr+hc));    //outer clothing temeperature  C

  /* Thermal Physiology */

  Res = Respiration(Rm,Ta,Pa,&Wres);    //watts/m^2  Wres=g/(h m^2)

  Skbf=SkinBloodFlow(Tc,Tsk);       //Liters/(h m^2)
  alpha=Alpha(Skbf);           //skin fraction of total weight

   Regsw=Sweat(Tc,Tsk,alpha); // g/(h m^2)
   Ersw=.68*Regsw;           // watts/m^2 assuming it all evaporates
   wet=Ersw/Emax;
   Edif = (1-wet)*.06*Emax;  //watts/m^2  diffusion through dry skin
   Wdif=Edif/.68;      // g/(h m^2)  rate of water loss by diffusion
   if (wet>=1) {
      wet=1;
      Wdif=0.;
      drip=(Wdif+Regsw)-(Emax/.68);  /* g/(h m^2) wasted sweat
                                          driping from skin */
      Wsk_evap=Wdif+Regsw-drip;  /* g/(h m^2) water evaporated from
                                          skin*/
   }
   else {
      drip=0;
   }

   // skin wettedness from sweating
   Wsk_evap=Regsw+Wdif;       //water vapor loss from skin  g/(hm^2)
   Esk=(.06+.94*wet)*Emax;
   RateOfTotalWaterLossPsqm=Regsw+Wres+Wdif; /* g/(h m^2) & Wres is
                                                 g/(h m^2) */
   RateOfTotalWaterLoss=RateOfTotalWaterLossPsqm*Adu; /* g/h
                                                includes dripping*/
```

```
            Wevap=Regsw+Wdif+Wres; //g/(h m^2)  total evaporation rate of
                                          water from person per m^2 */
            PSIc=MoranPSI( Tc,Tco, HR,  HRrest);
              //PSIsk=BowlingPSI(Tsk,Tsko,HR,HRrest);

            HSCR = Core(Tc,Tsk,met,Res,&heatFlowCoreToSkin,Skbf,&Rm,&Bfat);
            HSSK = Skin(wet,Dry,Emax,&heatFlowCoreToSkin);

            /* thermal capacity */
            TCCR=.97*(1-alpha)*Wt;
            TCSK=.97*alpha*Wt;

            if (MTIM>=PrintTime)
            {
               printf("\n%6.1f %5.1f %4.2f%4.0f %5.1f %5.3f %5.2f %5.2f %4.1f
%5.2f %3.2f %3.0f %8.2f %4.1f", ",TIM,Ta,clo,RH,Tdpa,Wo,Tc,Tsk,Rm/58.2,
Regsw/60*Adu,wet,HR,CWLL,PSIc);
               fprintf(pofile,"\n%6.1f %5.1f %4.2f%4.0f %5.1f %5.3f %5.2f
%5.2f %4.1f %5.2f %3.2f %3.0f %8.2f%8.2f.%4.1f",TIM,Ta,clo,RH,Tdpa,Wo,Tc,Tsk,
Rm/58.2,Regsw/60*Adu,wet,HR,CWLL,CdripL,PSIc);

            PrintTime=ExTime+DTMP/60; /* next print time & ExTime in hr,
                                         DTMP is print interval in hr */
            }
            TIM +=DT; // hr

            // Tc and Tsk after time step DT
            Tc +=HSCR*Adu/TCCR*DT;
            Tsk +=HSSK*Adu/TCSK*DT;
            Ta=Ta+(Ta_rise/24)*DT;
            MRT=Ta;
 CumulativeWaterLossPsqm=CumulativeWaterLossPsqm+RateOfTotalWaterLossPsqm*DT;
            CumulativeWaterLoss=CumulativeWaterLoss+RateOfTotalWaterLoss*DT;
                                                                     // g
            CWLL=CumulativeWaterLoss/1000;   //Liters water liq+evap
            CEvapWL = CEvapWL + Wevap*Adu*DT;    //g
            CEvapWLL = CEvapWL/1000;             //Liters evap
            CdripL = CdripL + drip*Adu*DT/1000;  //Liters drip
           //-----------------------------------------------------------------

            Wo=Wi+CWLL/ma;  // kgw/kga, 1 Lw = 1 kgw
            Pa=Wo*Pbar*((Ta+273)/(Tao+273))/(Wo+.622);   /* new Pa  torr with
                                              new Pb=Pbar*(Ta+273)/(Tao+273)*/
            Psa=SatVapPres(Ta);

            if (Pa>Psa){
               Pa=Psa;
               Wos=.622*Pa/(Pbar-Pa);  // kgw/kga saturated humidity ratio
               Wo=Wos;
            }

            RH=Pa/Psa*100;
            Tdpa=4030.183/(18.6686-log(Pa))-235;
            ExTime+=DT;  //hr
      }  //return to while

      fclose(pifile);  //close inputfile
```

```
      fclose(pofile);  //close outputfile
      return 0 ;
}

void OutputHeader()
{
      printf("\n hr     Ta    clo    RH    Tdp    Wo    Tc     Tsk    met    sw    wet
HR    CWLoss PSI \n");
      printf("          C              C   kgw/kga   C      C          g/min
bpm      L\n");
      return ;
}

double SatVapPres(double T)
{
      double Pst;
            Pst = exp(18.6686-(4030.183/(T+235.)));  //mmhg
      return Pst;
}

double Convection(double met,double V)
{
      double CHCA, CHCV, CHCmin, hc;
      CHCmin = 3.0;
      if (met>=1.1) {
         CHCA = 5.66*pow((met - 0.85),0.39); /* hc due to activity */
      }
      else {
       CHCA = 5.66*pow((1. - 0.85),0.39); /* hc due to activity */
      }
      CHCV = 8.6*pow(V,0.53);              /* hc due to air speed V in m/s */
            if (CHCV >= CHCmin)
                  ;
            else
                  (CHCV = CHCmin);
            if (CHCV >= CHCA)
                  hc = CHCV;
            else
                  hc = CHCA;
      return hc;
}

double Respiration(double Rm, double Ta, double Pa,double*Wres)
{
      double Res,Eres,Cres;
      Eres = 0.0023*Rm*(44.-Pa);  /* watts/m2 */
      Cres = 0.0014*Rm*(34.-Ta);  /* watts/m2 */
      *Wres=Eres/.68;        /* g/(h m^2) */
      Res = Eres + Cres;
      return Res;
}

double DuBoisSkinArea(double Wt, double Ht)
{
      double Adu; /* m^2 */
      Adu=0.202*pow(Wt,0.425)*pow(Ht,0.725);/*Wt weight in kg, Ht height in
                                                         m. */
```

```
	return Adu;
}

double BflowCore(double Rm, double HRRk)
{
	double BFcr,BFcrmax;
	BFcrmax=.92*Clave;  // ml/(m^2*min)
	if(Rm/58.2<=1.3){    //if at rest
		if (HRRk>.25)
			BFcr=BFcrmax*(1-1.266*(HRRk-.25));
		else
			BFcr=BFcrmax;
	}
	else                    //during exercise
	{
		if (HRRk>.39)
			BFcr=BFcrmax*(1-1.0866*(HRRk-.39));
		else
			BFcr=BFcrmax;
	}
	return BFcr;    //ml/(min*m^2)
}

double BflowMuscle(double Rm,double Bfc)
{
	double mcr,mmu,BFmu;
	mcr=Bfc*BLO2cap*FO2ExtCr/O2equiv;
	mmu=Rm-mcr;
	BFmu=mmu*O2equiv/(FO2ExtMu*BLO2cap); /*muscle bloodflow in
	                                      mlblood/(min*m^2) */
	return BFmu;
}

double StrokeVolume(double Adu, double HRrest,double Tsk)
{
	double SV1,SV;
	SV1=Clave*Adu/HRrest;  //stroke volume ml
	if (Tsk<=33)
	   SV=SV1;
	else
	{
	   if (Tsk<38)
	      SV=SV1-5*(SV1-85)*(Tsk-33)/45;
	   else
	      SV=SV1-5*(SV1-85)*(38-33)/45;
	}
	return SV;
}

double Shiver(double Tc, double Tsk,double*Bfat)/*Tikusis & Stolwijk Models*/
{
	double shiver=0;    // Bfat is % body fat
	if (Tc<TTCR || Tsk<33)                /* does shiving occur? Tc<37/*/
	{  if (Tc<TTCR && Tsk<33)            /*shiver diven by core and skin*/
	      shiver=(156*(TTCR-Tc)+47*(33-Tsk)-1.57*pow((33-
Tsk),2))/pow(*Bfat,0.5); /*Tikusis and Giesbrecht,1999,15%BFat */
	   else
```

```
            if(Tc<TTCR)   /*shiver driven core only*/
              shiver=(156*(TTCR-Tc))/pow(*Bfat,0.5);
            else
              shiver=(47*(33-Tsk)-1.57*pow((33-Tsk),2))/pow(*Bfat,0.5);
                                                      //driven by skin only
      }
      //shiver=0;      /*Use to disable shiver*/
      return shiver;
}

double MetT(double HR,double HRrest,double T) //Berglund,30th ACEMB 1977
{
      double met,HRratio;  /* applicable:20<=T<=40, 0.6clo, v~=1.25m/s,
                              1.2<+HRratio<=2.1,Tdp<=20C*/
      HRratio=HR/HRrest;
      if (HRratio>=1.2) {
         if (T>=20)
            met=0.68+4.69*(HRratio -1)- 0.052*(HRratio-1)*(T-20);
         else
            met=0.68+4.69*(HRratio -1);
      }
      else {
            met=HRratio;
      }
      return met;
}

double BreathRate(double Xmet, double Wt, double Adu) /*aerobic breathing
rate for metabolism*/
{
      double Bf, VO2pkg;
      VO2pkg=Xmet*58.2*O2equiv*Adu/Wt;
      Bf=.3957*VO2pkg+18.735;
      return Bf;
}

double HeartRate(double met,double T, double HRrest) /*from Berglund 30th
                                                        ACEMB,1977 */
{
      double HRratio,HR;
      HRratio=1+(met-.68)/(4.69- 0.052*(T-20));
      HR=HRrest*HRratio;
      return HR;
}

double Alpha(double Skbf)
{
      double alpha;
      alpha=0.04177+.74518/(Skbf+0.585417);
      return alpha;
}

double Sweat(double Tc, double Tsk, double alpha)
{
      double regsw, Tmb;
      regsw=0;
      Tmb=(1-alpha)*Tc + alpha*Tsk;
```

```
      if ((Tmb>TTBM)&&(Tsk>TTSK))
         regsw=CSW*(Tmb-TTBM)*exp((Tsk-TTSK)/10.7);
      else if ((Tmb>TTBM)&&(Tsk<=TTSK))
                  regsw=CSW*(Tmb-TTBM);
      if (regsw>667)      // max sweat rate limit
         regsw=667;  // regsw_max=667g/(h m^2)=11.1g/(min m^2)!=20g/(min m^2)
      return regsw;  //g/(h m^2)
}

double SkinBloodFlow(double Tc, double Tsk)
{
      double Colds=0;
      double Skbf, WarmC=0;
      if (Tsk<TTSK)
            Colds=TTSK-Tsk;
      if (Tc>TTCR)
            WarmC=Tc-TTCR;
      Skbf=(SKBFN+CDIL*WarmC)/(1+CSTR*Colds);  // Liters/(h m^2)
      if (Skbf>Skbfmax)
            Skbf= Skbfmax;
      if (Skbf<Skbfmin)
            Skbf= Skbfmin;
      return Skbf;           //L/(h m^2)
}

double Core(double Tc,double Tsk,double met,double Res,
      double*heatFlowCoreToSkin, double Skbf,double*Rm,double*Bfat)
{
      double Rmet, Hfcrsk,HSCR,shiver;
      shiver=Shiver(Tc,Tsk,Bfat);              /* watts/m^2 */
      Hfcrsk=(CMIN+CB*Skbf)*(Tc-Tsk);     /* watts/m^2 */
      Rmet = 58.2*met + shiver;     /* metabolic heat produced watts/m^2 */
      HSCR=Rmet-Hfcrsk-Res;  /* rate of heat storage in core  watts/m^2 */
      *heatFlowCoreToSkin=Hfcrsk;
      *Rm=Rmet;

      return HSCR;    //rate of heat storage in core compartment w/m^2
}

double Skin(double wet,double Dry,double Emax,double*heatFlowCoreToSkin )
{
      double Esw,Ediff,Esk,HSSK;
      Esw=wet*Emax;
      Ediff=.06*(1-wet)*Emax;
      Esk=Esw+Ediff;
      HSSK=*heatFlowCoreToSkin-Dry-Esk;/*rate of heat storage in skin w/m^2*/
      return HSSK;
}

double MoranPSI(double Tc,double Tco,double HR, double HRrest)
{
      double PSI;
      PSI=5*((Tc-Tco)/(39.5-Tco)+(HR-HRrest)/(180-HRrest));
      return PSI;
}

/* This is the End */
```

```
/*
Example of Input and resulting output files of Sub_ICDA

 Input file name: Subin3.txt
hr          met
 1.          1.
 2.          1.
 3.          1.
 4.          1.
 5.          1.
 6.          1.
 7.          1.
 8.          1.

Output:
output file name:             SubOut3bVps_RH.txt
 Air Volume(m^3)= 360.000000, V(m/s)= 0.050000, dTa/dday=  1.110000
 wt(kg)= 82.000000, ht(m)= 1.770000,  Bfat= 15.000000

hr      Ta   clo  RH  Tdp   Wo    Tc    Tsk  met  sw  wet   HR CWLos CdripL PSI
        C             C           C      C        g/min     bpm   L     L
  0.0 24.0 0.20  60 15.8 0.011 36.90 33.00 1.0  0.00 0.06 70    0.0    0.0  0.0
  6.0 24.3 0.20  62 16.5 0.012 36.90 32.48 1.1  0.00 0.00 74    0.2    0.0  0.2
 12.0 24.6 0.20  63 17.1 0.012 36.89 32.59 1.1  0.00 0.00 74    0.4    0.0  0.2
 18.0 24.8 0.20  65 17.8 0.013 36.89 32.70 1.1  0.00 0.00 74    0.6    0.0  0.1
 24.0 25.1 0.20  66 18.3 0.013 36.88 32.81 1.0  0.00 0.00 73    0.8    0.0  0.1
 30.0 25.4 0.20  67 18.9 0.014 36.88 32.92 1.0  0.00 0.00 73    1.0    0.0  0.1
 36.0 25.7 0.20  68 19.4 0.014 36.87 33.06 1.0  0.00 0.00 73    1.2    0.0  0.1
 42.0 25.9 0.20  70 19.9 0.015 36.88 33.34 1.0  0.00 0.00 73    1.4    0.0  0.1
 48.0 26.2 0.20  71 20.4 0.015 36.88 33.57 1.0  0.03 0.00 74    1.5    0.0  0.1
 54.0 26.5 0.20  72 21.0 0.015 36.88 33.63 1.0  0.11 0.02 74    1.8    0.0  0.1
 60.0 26.8 0.20  73 21.5 0.016 36.88 33.70 1.0  0.19 0.03 74    2.0    0.0  0.1
 66.0 27.1 0.20  75 22.1 0.017 36.88 33.75 1.0  0.28 0.05 74    2.2    0.0  0.1
 72.0 27.3 0.20  76 22.8 0.017 36.89 33.81 1.0  0.37 0.07 74    2.5    0.0  0.2
 78.0 27.6 0.20  78 23.5 0.018 36.89 33.86 1.0  0.46 0.09 74    2.8    0.0  0.2
 84.0 27.9 0.20  80 24.2 0.019 36.90 33.91 1.0  0.55 0.12 74    3.1    0.0  0.2
 90.0 28.2 0.20  82 24.9 0.020 36.91 33.97 1.0  0.65 0.14 74    3.5    0.0  0.2
 96.0 28.4 0.20  85 25.6 0.021 36.91 34.03 1.0  0.75 0.18 74    3.9    0.0  0.2
102.0 28.7 0.20  87 26.4 0.021 36.92 34.08 1.0  0.84 0.21 74    4.3    0.0  0.2
108.0 29.0 0.20  90 27.2 0.023 36.93 34.14 1.0  0.94 0.26 75    4.7    0.0  0.3
114.0 29.3 0.20  93 27.9 0.024 36.93 34.19 1.0  1.05 0.31 75    5.2    0.0  0.3
120.0 29.5 0.20  95 28.7 0.025 36.94 34.25 1.0  1.15 0.38 75    5.6    0.0  0.3
126.0 29.8 0.20  98 29.5 0.026 36.95 34.31 1.0  1.25 0.47 75    6.1    0.0  0.3
132.0 30.1 0.20 100 30.1 0.027 36.96 34.36 1.0  1.35 0.56 75    6.7    0.0  0.3
138.0 30.4 0.20 100 30.4 0.028 36.96 34.41 1.0  1.44 0.63 75    7.2    0.0  0.4
143.9 30.7 0.20 100 30.7 0.028 36.97 34.46 1.0  1.52 0.70 75    7.8    0.0  0.4
149.9 30.9 0.20 100 30.9 0.029 36.98 34.50 1.0  1.61 0.78 75    8.4    0.0  0.4
155.9 31.2 0.20 100 31.2 0.029 36.98 34.55 1.0  1.70 0.87 76    9.0    0.0  0.4
161.9 31.5 0.20 100 31.5 0.030 36.99 34.60 1.0  1.79 0.98 76    9.7    0.0  0.4
167.9 31.8 0.20 100 31.8 0.030 37.02 34.80 1.0  2.16 1.00 76   10.4    0.0  0.5
173.9 32.0 0.20 100 32.0 0.031 37.07 35.05 1.0  2.67 1.00 77   11.3    0.2  0.6
179.8 32.3 0.20 100 32.3 0.031 37.12 35.30 1.0  3.24 1.00 78   12.3    0.6  0.8
185.8 32.6 0.20 100 32.6 0.032 37.18 35.56 1.0  3.87 1.00 79   13.6    1.2  0.9
191.8 32.9 0.20 100 32.9 0.032 37.26 35.81 1.0  4.59 1.00 80   15.2    2.1  1.1
197.8 33.1 0.20 100 33.1 0.033 37.34 36.06 1.0  5.42 1.00 81   17.0    3.2  1.4
203.8 33.4 0.20 100 33.4 0.033 37.44 36.31 1.0  6.37 1.00 83   19.1    4.7  1.6
209.8 33.7 0.20 100 33.7 0.034 37.56 36.56 1.0  7.45 1.00 84   21.6    6.5  1.9
```

```
215.7 34.0 0.20 100 34.0 0.034 37.69 36.81 1.0  8.69 1.00 86  24.5   8.7  2.3
221.7 34.3 0.20 100 34.3 0.035 37.84 37.07 1.0 10.10 1.00 88  27.9  11.4  2.6
227.7 34.5 0.20 100 34.5 0.036 38.00 37.32 1.0 11.68 1.00 91  31.8  14.6  3.1
233.7 34.8 0.20 100 34.8 0.036 38.18 37.57 1.0 13.43 1.00 93  36.3  18.5  3.5
239.7 35.1 0.20 100 35.1 0.037 38.37 37.82 1.0 15.36 1.00 96  41.4  23.0  4.0
245.7 35.4 0.20 100 35.4 0.037 38.58 38.07 1.0 17.52 1.00 97  47.3  28.2  4.5
251.6 35.6 0.20 100 35.6 0.038 38.84 38.32 1.0 20.14 1.00 97  54.1  34.2  5.0
257.6 35.9 0.20 100 35.9 0.039 39.10 38.58 1.0 22.10 1.00 97  61.8  41.2  5.5
263.6 36.2 0.20 100 36.2 0.039 39.35 38.84 1.0 22.10 1.00 97  69.7  48.5  6.0
269.6 36.5 0.20 100 36.5 0.040 39.61 39.10 1.0 22.10 1.00 97  77.7  55.8  6.5
275.6 36.7 0.20 100 36.7 0.040 39.87 39.35 1.0 22.10 1.00 97  85.6  63.0  7.0
281.6 37.0 0.20 100 37.0 0.041 40.13 39.61 1.0 22.10 1.00 97  93.6  70.3  7.5
287.6 37.3 0.20 100 37.3 0.042 40.39 39.87 1.0 22.10 1.00 97 101.5  77.5  8.0
293.6 37.6 0.20 100 37.6 0.042 40.65 40.13 1.0 22.10 1.00 97 109.5  84.8  8.5
299.6 37.9 0.20 100 37.9 0.043 40.92 40.39 1.0 22.10 1.00 97 117.4  92.0  9.0
305.6 38.1 0.20 100 38.1 0.044 41.18 40.65 1.0 22.10 1.00 97 125.4  99.3  9.5
311.6 38.4 0.20 100 38.4 0.045 41.44 40.91 1.0 22.10 1.00 97 133.3 106.5 10.0
317.6 38.7 0.20 100 38.7 0.045 41.70 41.17 1.0 22.10 1.00 97 141.2 113.7 10.5
323.6 39.0 0.20 100 39.0 0.046 41.96 41.43 1.0 22.10 1.00 97 149.2 121.0 11.0
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